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ROBOTIC PAINT STRIPPING CELL

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The purpose of this work has been to develop a robotic system for stripping paint from F-16 aircraft using non-chemical means and to integrate the system at Ogden Air Logistics Center (OO-ALC). The Robotic Paint Stripping Cell (RPSC) is an automation system consisting chiefly of two large robots developed for removal of paint from fighter-size aircraft and aircraft components using the plastic media blast (PMB) process. The system was installed at Hill AFB in the Plastic Media Blast Booth at Building 220 and put into production use by the Air Force in September 1992.

The technical effort on this project resulted in the development of an automated system incorporating two robots of unique kinematic design especially suited for paint stripping and general surface processing of fighter-size aircraft. A more consistent paint stripping quality is achievable with the sensor-based, computer-controlled robotic plastic media blast system than is possible using manual methods. The sensor-based controls are used for all F-16 substrate materials, including graphite-epoxy composites. The RPSC is a fully automated plastic media blast paint stipping system, providing improvement of operator health and safety conditions by removing them from the blast environment.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

EXECUTIVE SUMMARY

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The technical effort on this project resulted in the development of an automated system incorporating two robots of unique kinematic design especially suited for paint stripping and general surface processing of fighter-size aircraft. A more consistent paint stripping quality has been achieved with the sensor-based, computer controlled robotic plastic media blast system than possible using manual methods. The sensor-based controls are used for all F-16 substrate materials, including graphite-epoxy composites. The RPSC is a fully automated plastic media blast paint stripping system, providing improvement of operator health and safety conditions by removing them from the blast environment.

This Final Report provides review of the project development phases, description of the developed system hardware, technical discussion of the robotic technology employed, presentation of the software-based operator interface, and overview of the system sequence of operations for automatic paint stripping.

1.0 INTRODUCTION

The Robotic Paint Stripping Cell (RPSC), as shown in Figure 1, is an automation system consisting chiefly of two large robots which remove paint from fighter size aircraft and aircraft components using the plastic media blasting (PMB) process. The system was developed by Southwest Research Institute (SwRI) of San Antonio, Texas under U.S. Air Force contract F33615-86-C-5044, Wright Laboratories. The system was installed at OO-ALC in the Blast Booth at the southeast corner of Building 220, and production use by the Air Force began in September 1992.

The development program involved a three-phase approach. Phase I required evaluation of candidate nonchemical paint stripping processes, testing of viable approaches, and recommendation of a process for implementation in Phase II. Development of hardware and software to automate the selected paint stripping process was accomplished in Phase II, along with modification of the OO-ALC blast booth to accommodate the robots. Phase III included installation of the RPSC at OO-ALC, application programming for F-16 aircraft, and training of operators and maintenance personnel.

The development program encompassed the following technical activities and milestones:

- Evaluation of candidate nonchemical paint stripping processes for Air Force selection of a technically suitable process.
- Laboratory testing of the selected process to determine operational and control parameters for automation of the process.
- Development of a materials test plan.
- Development of automation concepts to implement the selected paint stripping process.
- Design of custom robots for the work cell.
- Development of a "paint sensor" for adaptive control of the robotic paint stripping process.
- Fabrication and testing of the RPSC hardware and software.
- Generation of site preparation requirements to accommodate the robotic system in the existing OO-ALC bead blast facility.
- Modification of the OO-ALC blast facility for automated PMB paint stripping.
- Development of documentation for system operation, hardware maintenance, and software support.
- Installation of the RPSC at OO-ALC.
- Application programming for the F-16 aircraft models and variants.
- Training of OO-ALC operation, maintenance, and supervision personnel.

Figure 1. The Robotic Paint Stripping Cell in Operation at OO-ALC

A summary description of the completed system is provided in the remainder of this introductory section, followed by a discussion of the major accomplishments of the project. A more detailed chronological overview of the development aspects of the project begins with Section 2.0.

1.1 Description of the System

Figure 2 shows a conceptual design of the RPSC, which was developed in the latter stages of Phase I after selection of the plastic media blast process. A robot of unique kinematic design would be developed which would allow the majority of the surface area of fighter-size aircraft to be reached for PMB paint stripping. A pair of these robots, one on either side of the aircraft, would operate on tracks that would be installed inside the blast facility so that the robots could move along the length of the aircraft. The robots would be sized to fit inside the existing facility at OO-ALC -- the pivoted column would allow the arm portion to be tucked back against the wall in order to allow the robot to pass between the wing tip and the wall, even though this gap is only approximately 3-1/2 feet. Minimal modification of the facility other than the addition of suitable floor tracks would be required. Figure 3 shows the relative size and clearances between the robots and the F-4 and F-16 aircraft that had to be accommodated, indicating the robot ability to reach over and under the wings, around jack stands, and along the fuselage in order to access approximately 95% of the total surface area for paint stripping.

Robots were thus developed during Phase II, with the realization of the original concept shown in Figure 4. This is a nine degree-of-freedom robot (nine axes), standing approximately 20 feet tall and weighing approximately 26,000 pounds. Axis 1 provides for motion along the track, while Axis 2 is a pivot of the links to which the column is attached. The combined movement of Axis 1 and Axis 2 allow the column to be positioned at an X-Y coordinate of the facility floor. Once the column is positioned as desired, both of these axes are locked (including locking of the upper column pivot joint by means of a large disk brake), and a stabilizing foot is forced against the floor to increase the stability of the column structure. A series of six coordinated axes then operate from the column to articulate the end effector. These begin with a vertical motion along the column (Axis 3), a shoulder pivot about the column centerline (Axis 4), an elbow (Axis 5), and three wrist pivots for yaw (Axis 6), roll (Axis 7), and pitch (Axis 8). A ninth servo axis is used to roll the tool (Axis 9) to allow additional dexterity for manipulation of the rather large end effector with attached, cumbersome blast hoses.

The robot incorporates PMB paint stripping equipment, consisting primarily of a blast pot mounted in the upper portion of the main structure and a specially-developed end effector. The robot blast pot connects to a media delivery system in the blast facility to maintain a constant supply of clean plastic media in the blast pot. Blast media is metered at the prescribed mass flow rate from the pressurized blast pot into three large hoses which transport the compressed air flow and entrained media to three 1/2 inch bore nozzles in the end effector. Provision is made for programmatically altering the blast pressure and media flow rate, while the robot arm maintains the surface standoff distance and selected orientation for blasting. Figure 5 shows the relative positioning of the end effector near the aircraft during the paint stripping process (shown during laboratory testing with an F-4 aircraft). Nominal surface standoff is 18 inches, although the blast process and controls are tolerant of a wide variation in this nominal value.

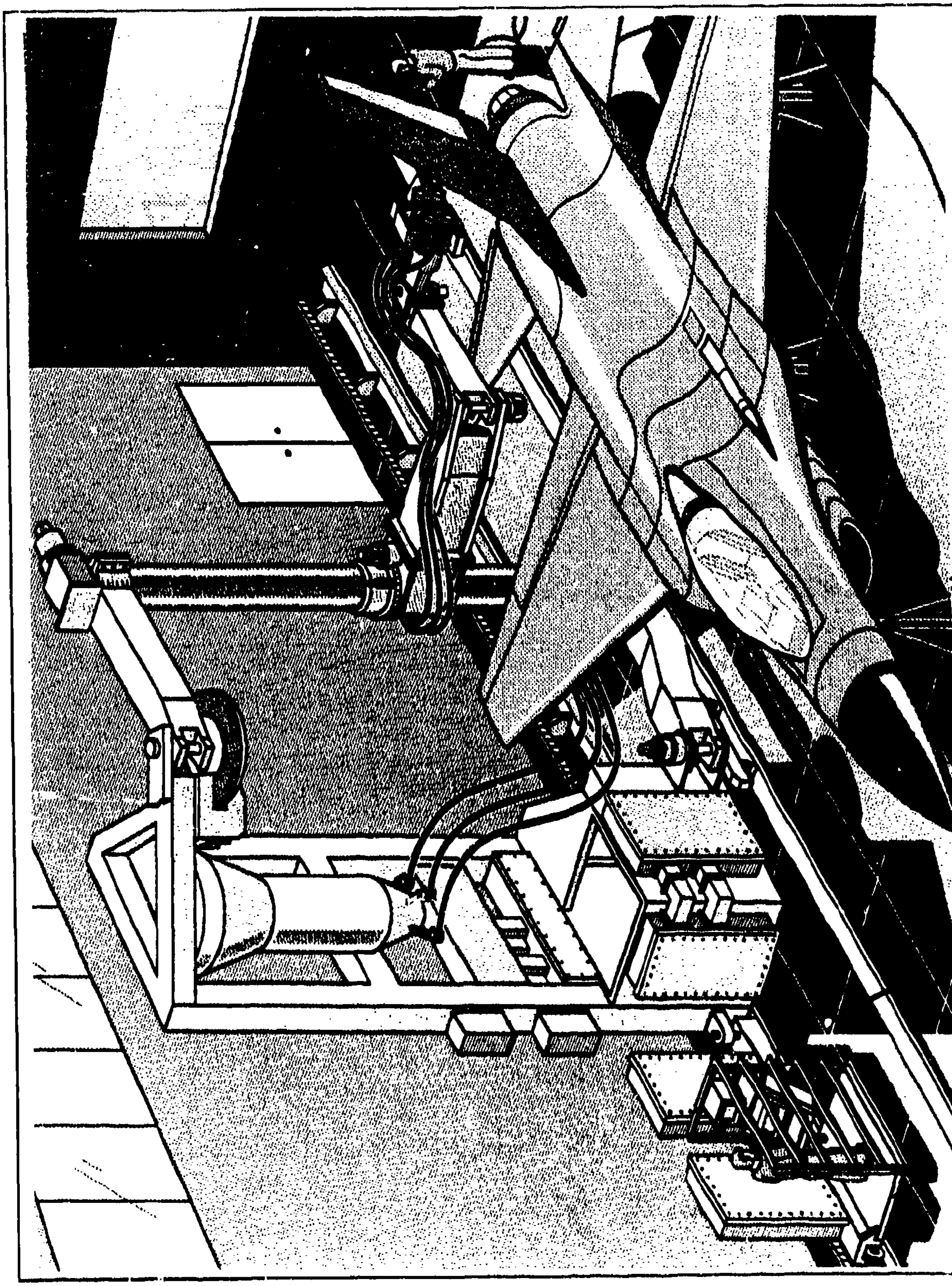


Figure 2. Artist's Concept of Automated Paint Stripping

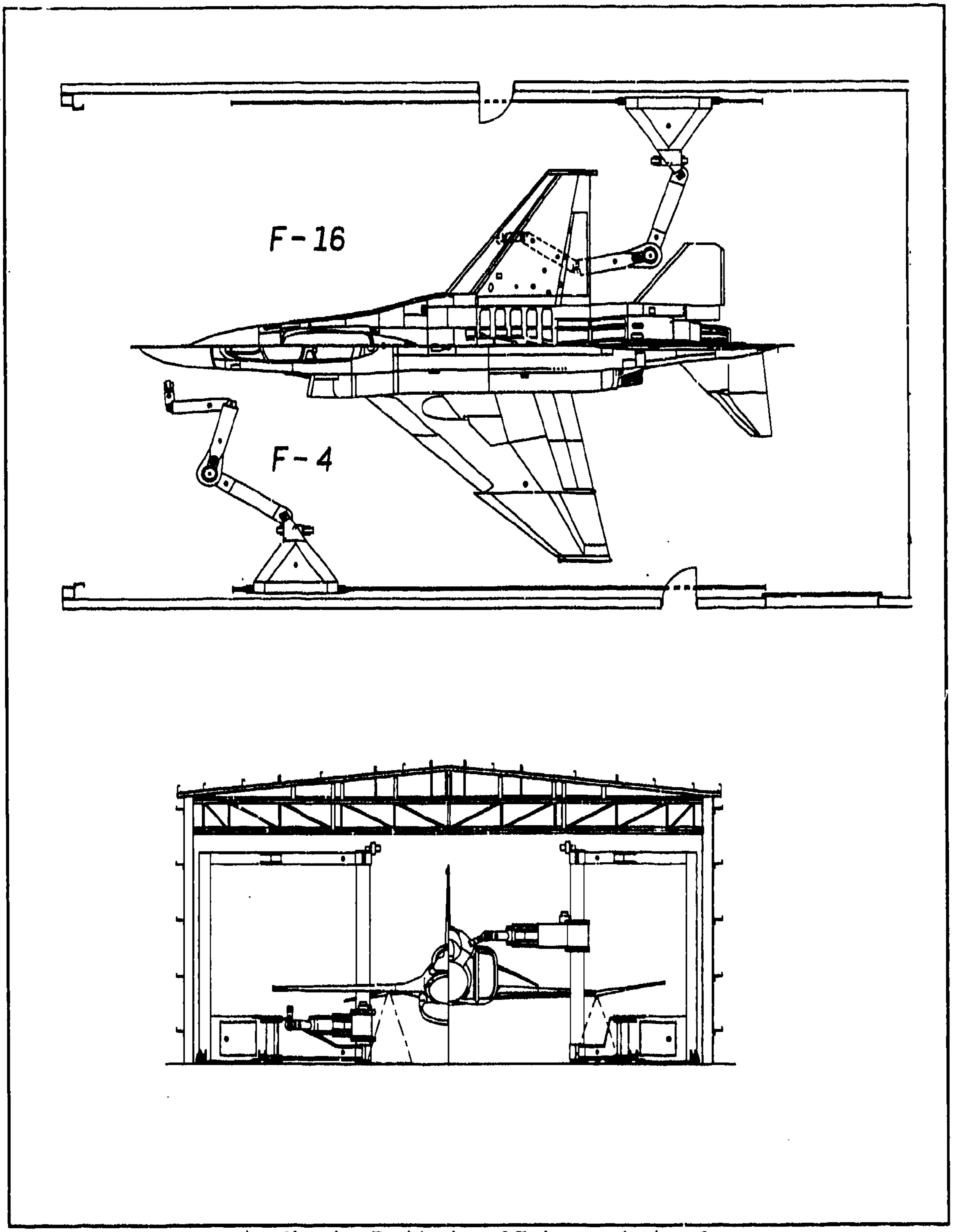


Figure 3. Layout Drawing Showing Positioning of Robots and Aircraft

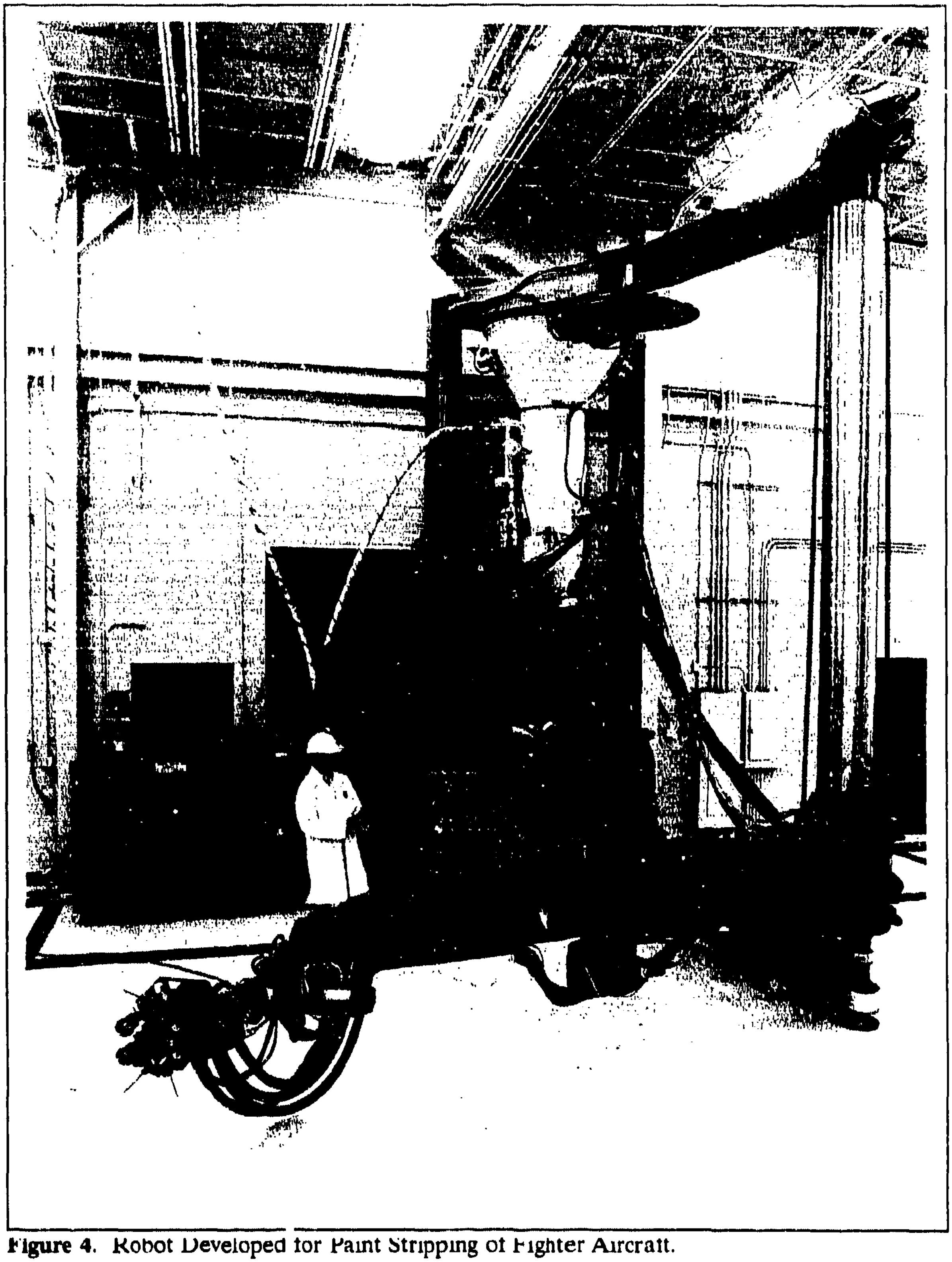


Figure 4. Robot Developed for Paint Stripping of Fighter Aircraft.

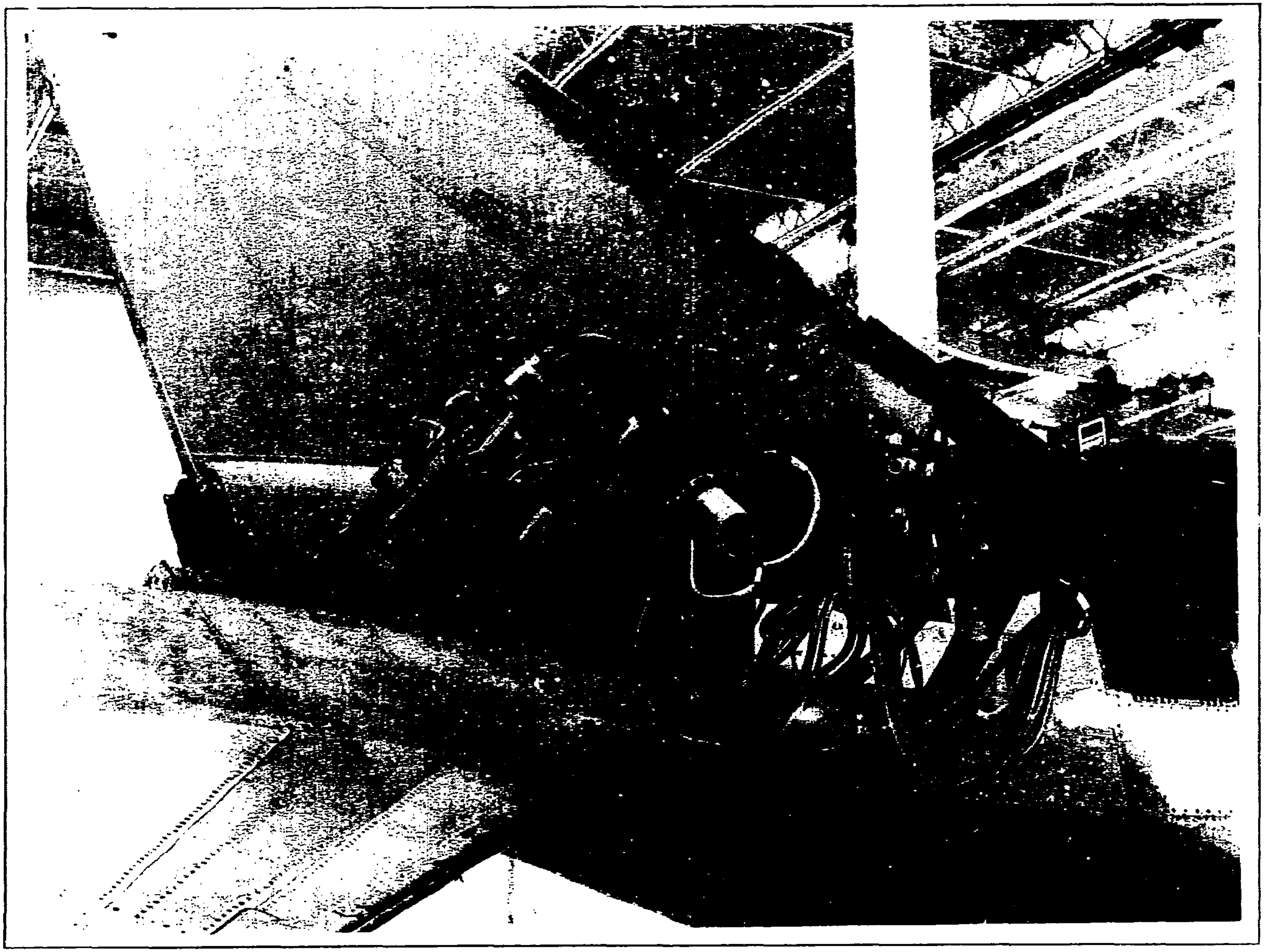


Figure 5. **Robot Demonstrating End Effector Orientation** for **Paint Stripping.**

Plastic media which is expelled from the end effector nozzles falls to the floor of the facility. The floor is covered with a grating over a series of funnel pans and air tubes so that the spent media finds its way to the air stream and is swept to a collection manifold and eventually into an accumulating hopper. The media is then cleaned with a sifter and a heavy particle separator. The cleaned media is then transported to another accumulating hopper. To transport the cleaned media back to a robot for reuse, a transport blower provides an air stream into which media can be metered and transported to the upper chamber of the robot blast pot. From there, two pressurized chambers allow the upper robot blast pot chamber to remain at atmospheric pressure while the lower chamber is held at the robot blast pressure for uninterrupted blasting while the blast pot is cycling and refilling.

The end effector (Figures 6 and 7) incorporates the SwRI-developed paint sensor which is used to adaptively adjust the path velocity of the robot to control the paint stripping rate and prevent overblasting of the substrate. Four halogen lamps provide an infrared-rich light source which is reflected from the stripping surface and received by a series of lens assemblies in the end effector. The reflected light is focussed onto a fiber optic bundle which transmits the light to photo-receptors in a protected electronics cabinet. An electrical conversion of the optical energy takes place, and signals received from two different infrared frequency bands are ratioed to provide information relating the amount of paint remaining in the footprint of the blast pattern. This computed "percent paint remaining" is used as the feedback to an adaptive motion control loop which alters the robot path velocity accordingly.

The blast swath from each of the robot nozzle triplets removes a width of paint of approximately 6 inches, at a nominal robot strip rate of 5 square feet per minute. The six blast nozzles used by the automated system (three on each robot end effector), provide approximately 2400 pounds per hour of media for the stripping process. Typical blast pressures used with the Type V acrylic media are 40 psi for aluminum and 30 psi for composite. The blast parameters can be selected by the process engineer for each material type.

To begin operation of the automated aircraft stripping, the aircraft is masked in the same manner as required for manual PMB to prevent media ingress. The aircraft is supported on jackstands so that the landing gear can be raised and the gear doors sealed. The operator selects the appropriate aircraft file at each robot and then teaches five reference points on the aircraft so that the software can translate and rotate the path file coordinates to match the pose of the aircraft. A self-check calibration procedure for the paint sensor system is then executed, and the actual stripping operation is initiated from an observation and control room.

Each robot incorporates its own control computer for execution of motion programs, and the pair of robots are coordinated by a cell controller which resides in an observation booth at the end of the blast area. The operator is able to observe both robots from this vantage point and to adjust path velocity control factors based on live video of the blast footprint from the end effector. "Exclusion zones" are defined for the robots so that collisions between the two robots are prevented by the cell controller, since the speed at which each robot completes its paint stripping sequence is dependent upon the condition of the paint in that region as monitored by the paint sensor.

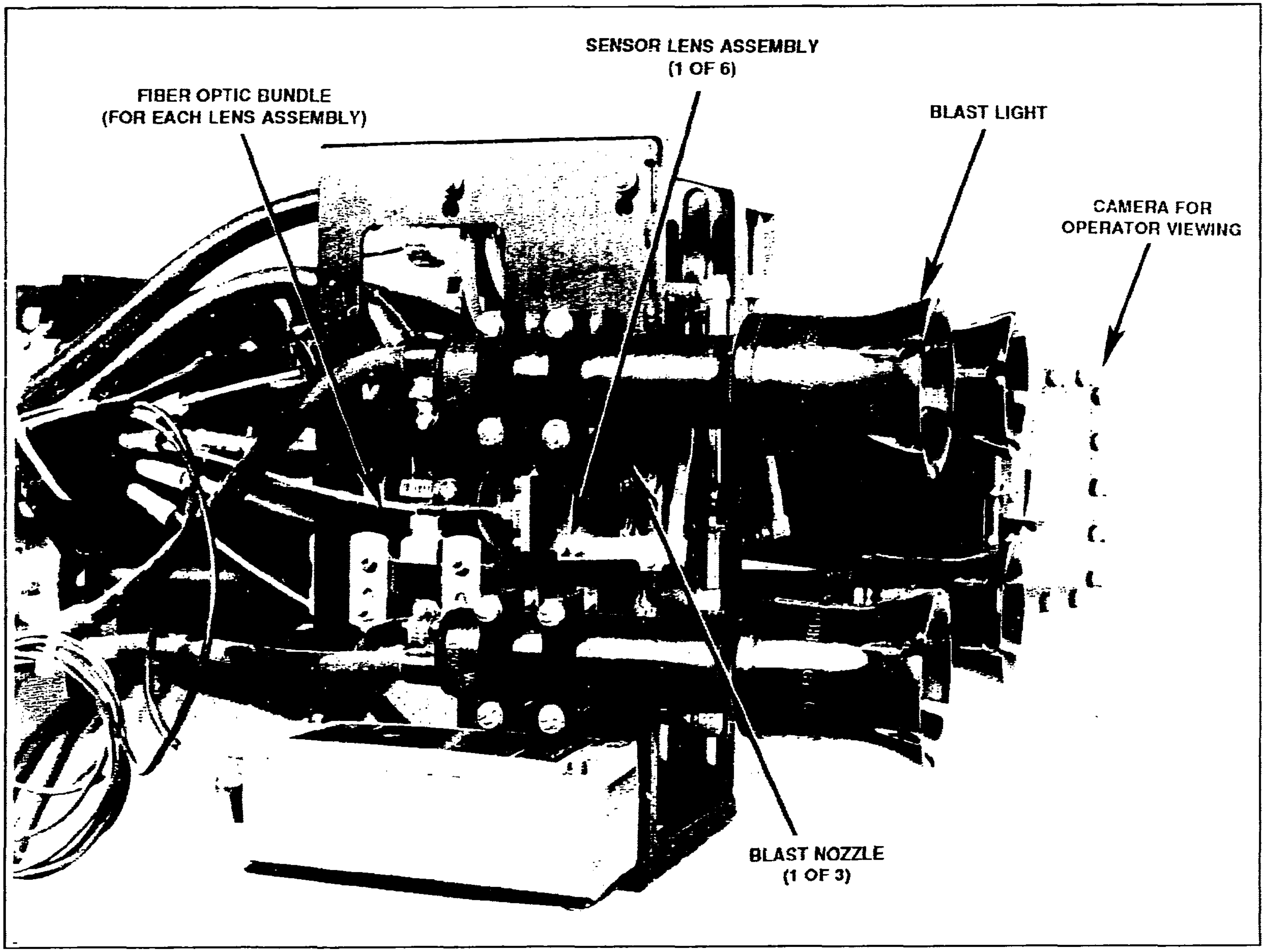


Figure 6. Plastic Media Blast End Effector (Side View)

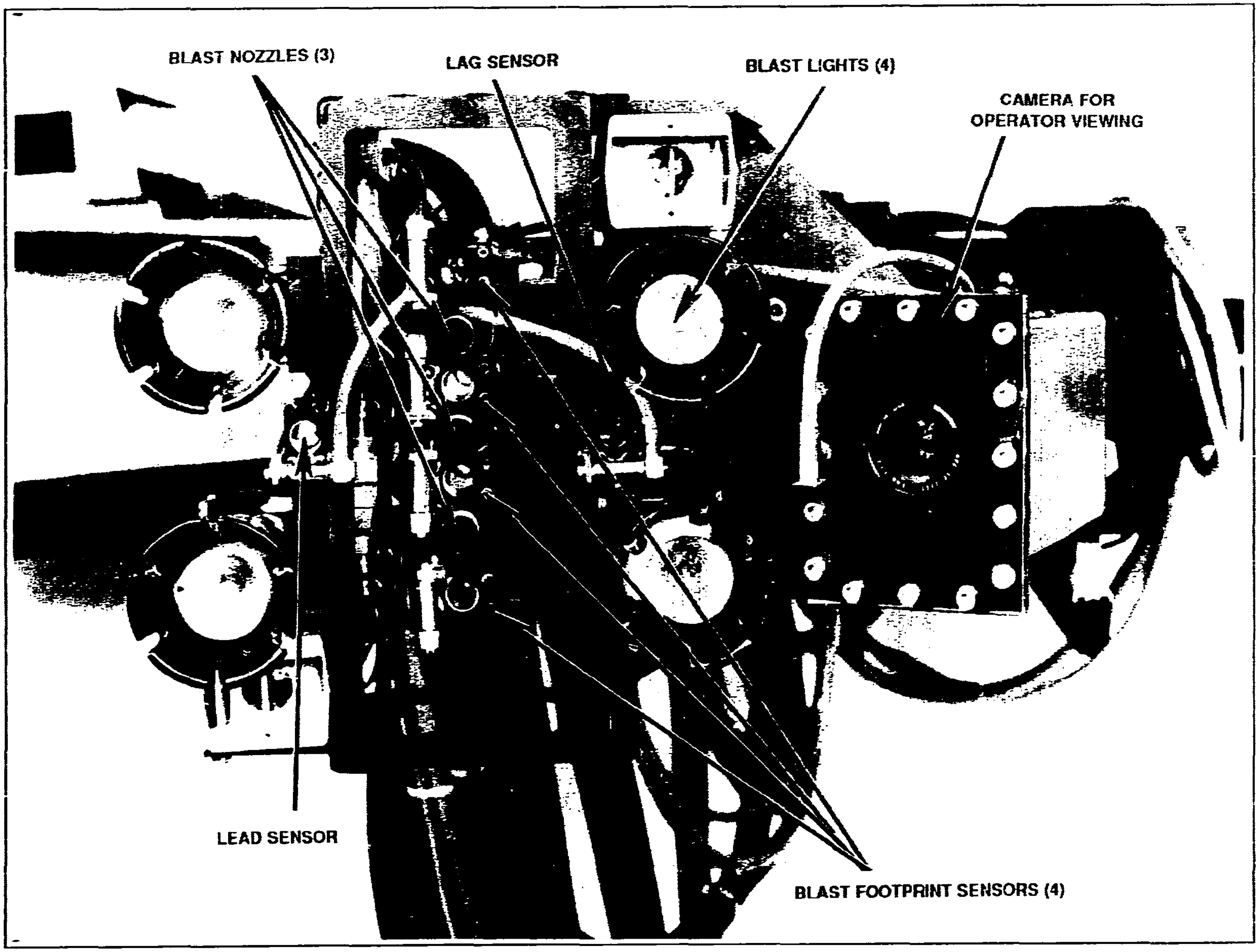


Figure 7. Plastic Media Blast End Effector (End View)

1.2 Major Technical Accomplishments

The technical efforts of this project resulted in the development for the Air Force of a unique robot suited for surface processing of fighter-size aircraft. A patent application has been filed for the robot design itself, as well as the use of the robot in an automated cell for paint stripping. The robot design provides a significant work volume from a relatively small physical size, requires few facility accommodations since it is freestanding, and addresses the requirements of accessing all major surfaces found on modern aircraft.

A unique paint sensor and adaptive control algorithm were developed to allow the automated use of PMB paint stripping on all common aircraft substrates, including the relatively delicate graphite fiber reinforced composites. U.S. Patent No. 5,038,038 "Optical Sensor for Detecting Quantity of Protective Coating" has been awarded for this technology.

The end product of the developmental project is a fully automated system for aircraft paint stripping, providing greater facility throughput and improvements for operator health and safety. Except for touch-up work, the requirement for operators to be in the dusty environment, wearing breathing suits, and climbing scaffolds while dragging heavy blast hoses is eliminated. Overblasting of the aircraft and component damage due to operator boredom and fatigue are eliminated by the automated system. A much more consistent paint stripping quality is achieved with the automated system than is possible with manual methods.

2.0 SYSTEM DESCRIPTION AND TECHNICAL DISCUSSION

This Section reviews the motivation for development of the automated paint stripping system, and summarizes the Phase I (process selection) and Phase II (design and development) project activities. Discussion is provided of the robotic technology incorporated into the RPSC to provide the high degree of process automation. The section concludes with a brief description of the sequence of operations involved in the automated paint stripping.

2.1 Motivation for Development of the RPSC

All USAF aircraft are scheduled into an Air Logistic Center for Planned Depot Maintenance (PDM) which includes an inspection and, if necessary, repainting of the aircraft exterior. If repainting is required, all of the paint must first be stripped from the aircraft. On the average, this complete paint stripping is required when there are five to seven coats of paint on the aircraft, resulting in complete paint stripping approximately every 5 years. Inspection of the airframe for cracks and corrosion is performed after the paint has been removed.

In the past, the most common method for stripping paint from aircraft has been to use chemical solvents (typically phenol solvents) to soften the organic coatings, followed by scrubbing and rinsing to remove the softened paint. Because of environmental and safety concerns, phenol solvents have been removed from the "allowed to use" list. The nonphenol replacements were found to be less effective and resulted in the coatings of paint being only partially removed. This necessitated an additional step in the stripping process to hand-sand essentially the entire aircraft to remove the residual coatings.

In addition to this less efficient means of paint removal, increasingly restrictive EPA and OSHA guidelines and standards regarding the use of methylene chloride chemicals and the disposal of resultant industrial waste products caused the USAF to seek an automated, nonchemical means of removing paint from aircraft and their major subassemblies. This led to the award to Southwest Research Institute of a contract from Wright Laboratories to develop the Robotic Paint Stripping Cell.

2.2 Paint Stripping Process Selection

The Phase I effort concentrated on evaluating various nonchemical paint stripping processes, including plastic media blasting, dry ice (CO_2) blasting, sanding, flash lamp, lasers, etc. to identify the technical feasibility of implementing one of the processes for the depot level maintenance operations at OO-ALC. The selected process would need to be compatible with the fighter aircraft maintained by OO-ALC, primarily the F-4 and F-16. This required that the selected paint stripping process be compatible with the substrate materials common to the target aircraft. Figures 8 and 9 indicate the wide variety of substrate materials in these two aircraft, which includes aluminums of various thicknesses, graphite/epoxy composite, titanium, and other lesser-used materials.

Plastic media blasting was selected by the Air Force as the nonchemical process to automate for removal of paint from the target Air Force aircraft. This is a pressurized blasting process using small plastic beads as the blast media, the media being selected to prevent damage to the aircraft substrates. At the end of the project Phase I, it had been determined that other technologies (see Table 1) were not as technically advanced and, thus, posed a much higher risk for process and control system development (note that the Table 1 "considerations" are circa September 1986 and do not take into account more recent developments). The plastic media blast process had been developed as a manual process at OO-ALC during the 1980's and became an integral part of OO-ALC depot maintenance facilities.

Table 1. Comparison of Alternative Nonchemical Stripping Processes (September 1986)

Process	Considerations
Plastic Media Blasting	• Hill AFB experience • Most mature process • Concern for use on composites
Water Jet Blasting	• Various pressures and with abrasives • Limited application experience for paint removal
Dry Ice (CO_2) Blasting	• Cryoblast (inconsistent test results) • Lockheed Clean Blast (process dropped) • Low strip rates from aluminum (.015 ft^2/min)
Flash Lamp	• Evaluations at SM-ALC • Residue build-up (complicates sensing) • Close tolerance to surface requires more precise robotics
Laser	• Preliminary laboratory testing Battelle InTA Plasmatronics • Lack of controllers
Sanding, Scotch Brite®	• Difficult to sense paint removal • Difficult to control
Liquid Nitrogen	• Ineffective on well bonded paint

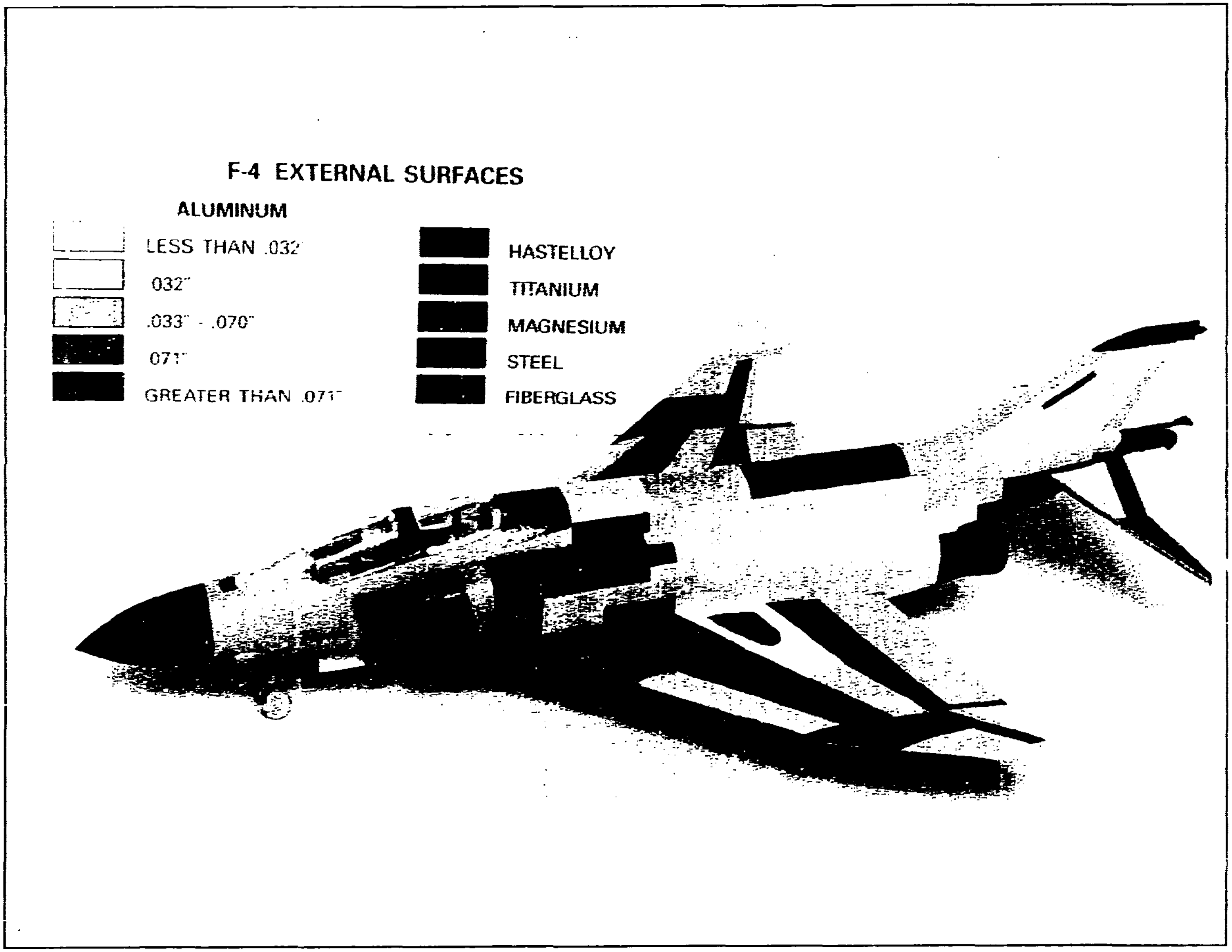


Figure 8. F-4 Aircraft Exterior Materials

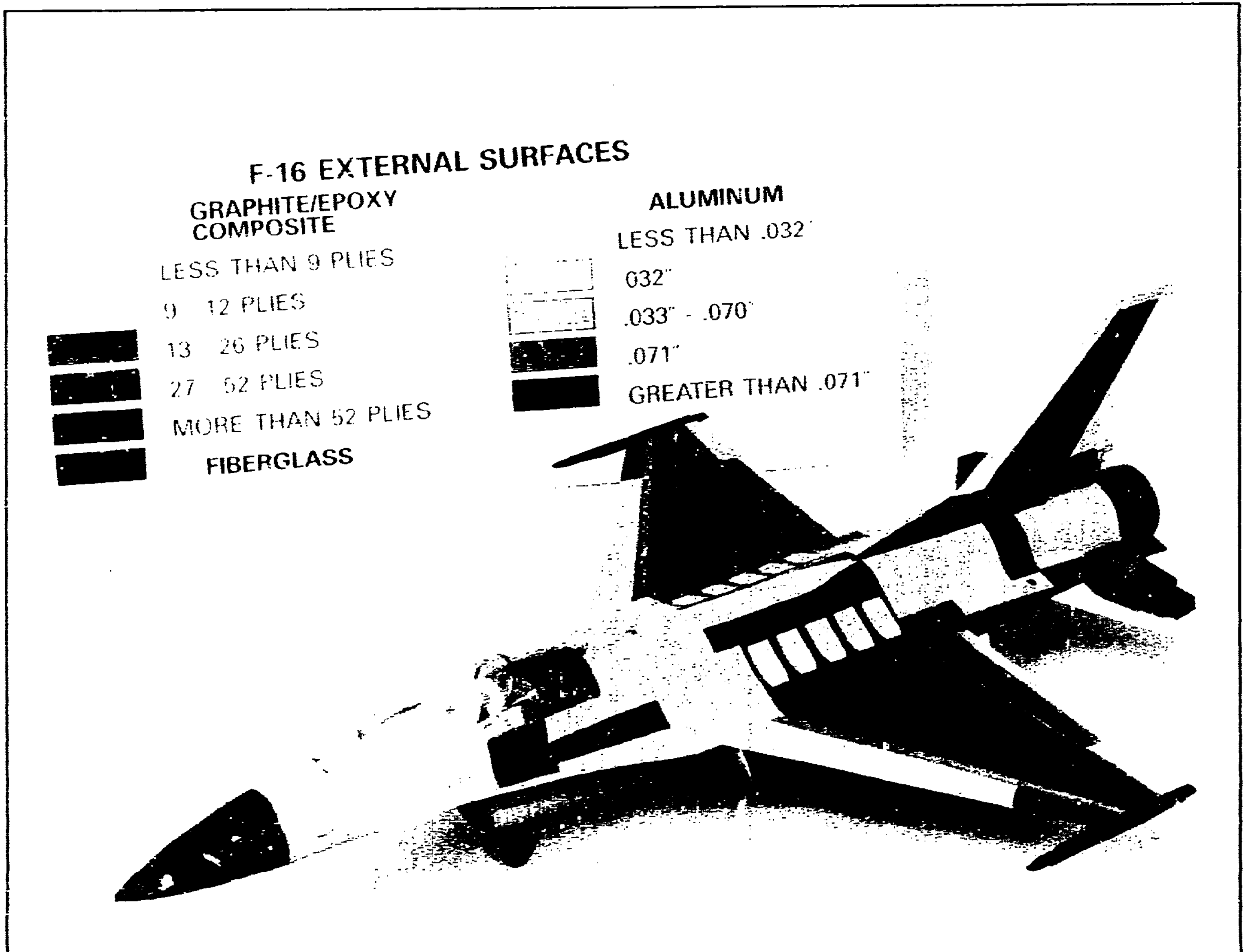


Figure 9. F-16 Aircraft Exterior Materials

The following observations regarding selection of the PMB paint stripping process were noted during the Phase I investigations circa July 1987:

- Commercially-available, industrially-hardened alternatives to plastic media blasting for the removal of paint from F-4s and F-16s do not exist at this time.

- The plastic media blast paint removal process was the only one capable of being automated at this time for this application with an acceptable level of risk for both metals and composites.

- Automating the plastic bead blast process does not preclude adapting the robotic cell to an alternative means of paint removal at a later date.

A materials test plan was prepared (final revision included as Appendix A) to evaluate process effects on aircraft substrates, building upon previously reported test results as documented in the test plan. After Air Force review of the test plans and revisions to increase the scope of the material testing, the Air Force ultimately elected not to fund the testing and instructed SwRI to proceed with system development.

After selection of the plastic media blast process, laboratory testing was performed at Southwest Research Institute to identify process control parameters necessary to automate the stripping operations. These tests were documented in the Process Optimization Report (included as Appendix B). A laboratory robot was used with commercially available blasting equipment, as shown in Figure 10, to provide accurate control of paint stripping parameters during the investigations. Testing of plastic media blasting under robotic control at the SwRI laboratories provided evidence that graphite-epoxy substrates could be stripped of paint without damage to the fibers or resin. Initial studies were conducted using Type II (urea formaldehyde) plastic media in the hardness range of 3.0 to 3.5 mho, as this was the approved media for use at OO-ALC. (However, the media used by OO-ALC was later changed to the recyclable Type V, acrylic, which became the standard for use with the RPSC.)

Various plastic media delivery systems were qualitatively evaluated in the laboratory using commercially available equipment, including centrifugal wheels, blast-n-vac nozzles, and conventional open nozzles. Wheel delivery systems were just being introduced to the market and, thus, were bulky, heavy (for robotic manipulation), and suffered from reliability problems. The large blast footprint displayed "hot spots" which would make sensing and control of the process more difficult. Blast-n-vac systems offered benefits for recovery of a large portion of the spent media at the nozzle, but required physical contact with the aircraft surface for sealing. With multiple nozzles required to achieve desired strip rates and the need to also enclose sensing electronics, the end effector would grow in size, thus, making it useful only for relatively flat open surfaces. The primary advantage of the conventional open nozzle was that surface standoff could range from approximately 12 to 24 inches without significant change in the stripping effectiveness, thus providing a large margin for error in programming and robot manipulation and a means to reach into difficult-to-access areas of the aircraft with the open blast stream. Since the intended installation site at Hill AFB was already equipped with a floor recovery system, recovery of media at the nozzle provided no significant benefit.

Figure 10. Laboratory Set-Up for Paint Stripping Process Development

After selection of a conventional open nozzle delivery system, a matrix of blasting tests was conducted to identify suitable ranges of operation for blast pressure, media flow rate, nozzle standoff distance, and nozzle orientation angles relative to the blast surface. This work was coordinated with the on-going development of manual blasting techniques at OO-ALC and applicable Air Force Technical Orders to encompass a wide range of operational process settings made possible by the robotic system. This work led to the development and testing of a prototype end effector, shown in Figure 11, which would provide a reasonably wide blast swath while keeping the overall dimensions of the end effector small to facilitate moving the tool around the aircraft. The selection of three nozzles was also partially determined by the performance capabilities of the media recovery and processing equipment at the OO-ALC blast facility to handle the volume of media which would result from continuous blasting from six nozzles (three nozzles on each of two robots).

2.3 Economic Analysis and Benefits Assessment

An economic analysis of the Robotic Paint Stripping Cell was completed by Applied Concepts Corporation (subcontractor) based on economic data provided by OO-ALC and system performance estimates available in June 1989. A favorable economic benefit for the automated system was indicated in spite of performance imporovements achieved with the manual PMB process, particularly for the F-16 aircraft ($15,307 savings per aircraft). A summary of the economic analysis may be found in Apendix C.

2.4 Design of the RPSC Robots

After laboratory testing of the PMB paint stripping process, the following requirements for the RPSC robot were developed for use during the Phase II effort to design the automation system:

- Nozzle Standoff: Due to the nature of the PMB process, the nozzle-to-surface standoff distance is not critical, ranging from 12 to 24 inches. The angular orientation of the nozzle can vary ±30 degrees from perpendicular without strongly affecting the paint removal efficiency.

- Repeatability/Accuracy: Because the aircraft can be located within the cell with reasonable accuracy and because the blast process is relatively forgiving, a robot global positioning accuracy on the order of ±2 inches is acceptable. Robot positioning repeatability of ±1/2 inch will be adequate to allow the teaching of aircraft reference points to accommodate aircraft that may be somewhat out of position.

- Robot Speed: Nozzle speeds over the aircraft surface during stripping operations will be 5 inches per second or less. However, teaching and manual operations would be made more efficient by being able to move at speeds up to 10 inches per second.

- Payload: An end effector consisting of 3 spray nozzles, standoff sensors, paint sensor, and collision detection hardware would have a combined weight of approximately 35 pounds. In addition, there would be blast reaction forces and tooling loads from large diameter pressurized blast hoses. Worst case analysis of robot joint positions for total loads yields a resultant payload equivalent of approximately 100 pounds.

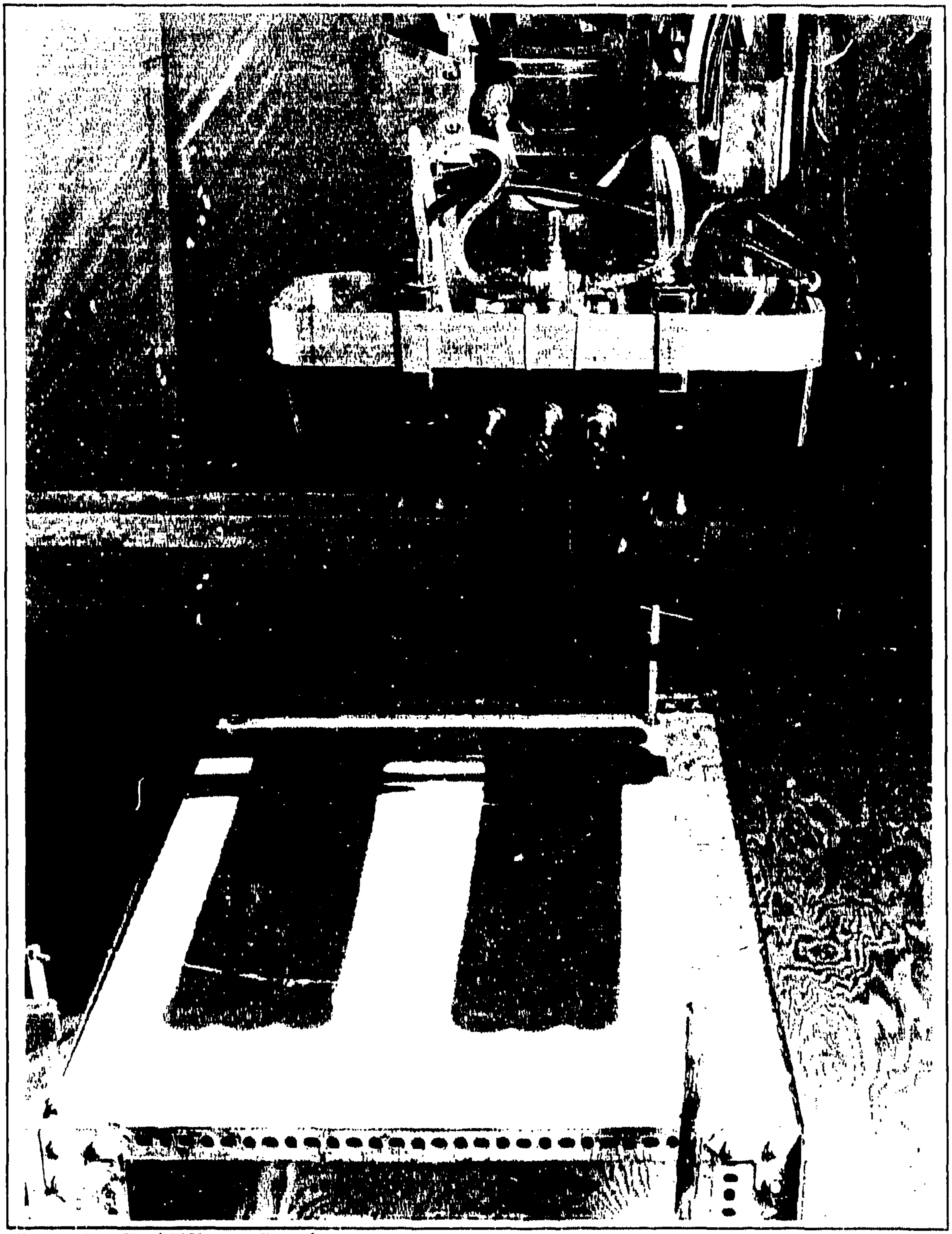


Figure 11. End Effector Development

- Operating Envelope: The approximate work envelope necessary for stripping an F-4 aircraft is 60 feet along the length of the aircraft, 38 feet across, and 17 feet vertically (assuming the jack stands support the plane 1 foot higher than normal landing gear height). The approximate work envelope for the F-16 aircraft is 48 feet along the length of the aircraft, 31 feet across, and 17 feet vertically.

- Installation Site: The existing bead blast facility at OO-ALC into which the robots and an F-4 must fit is 75 feet in length, 45 feet across, and 20.5 feet vertically.

The challenge in choosing a robot to satisfy these requirements lays in the physical constraints of the facility into which the RPSC would be installed. The primary restriction was the width of the F-4 at 38 feet versus the maximum width of the building at 45 feet (3.5 feet of clearance on either side of the aircraft). In order for the robot to move from the forward part of the aircraft to the aft section, it would be necessary to pass through this three foot passage. No commercially available robot was identified that is able to do this and still have the required reach and payload capacity. Alternatives, such as overhead gantries, automatic guided vehicles, multiple pedestal robots, and tracked robots were considered but found to be either lacking in the required capabilities or difficult to implement.

The approach which offered the preferred solution was to develop a robot design especially suited for moving along the surfaces of fighter sized aircraft and able to operate in the confined space of the existing OO-ALC facility. This approach resulted in the design of a wall-hugging robot traveling along floor mounted tracks installed next to the walls of the hanger. A robot of this design would be able to move between the aircraft wing tip and the hanger wall and reach out slightly past the centerline of the aircraft. The chosen design allows implementation of either 1-robot or 2-robot paint stripping cells. With a single robot installed on one side of the facility, the aircraft would be moved into the facility and one side (half of the aircraft) would be stripped first. The plane would then be taken out of the hanger, turned around, and brought back into the facility with the opposite side toward the robot to complete the stripping. A two robot implementation would use robots along both facility walls, each working on opposite sides of the aircraft.

A control computer would direct the robots along paths that have been pretaught for each type of aircraft. Each robot manipulates an end effector that includes three bead blast nozzles and suitable sensors. As the robot slowly moves the nozzles over the surface, a paint sensor would monitor the area being stripped. The sensor data would be analyzed to determine the amount of paint remaining on the substrate to be removed. This information would be used to increase the speed of the robot when paint is being removed rapidly or to slow down the robot in regions where thicker paint requires more time for paint removal. This would result in one-pass paint removal, minimizing overexposure of the aircraft material.

3.0 RPSC Robot System Description

This section describes the RPSC hardware, including process-related equipment for the paint stripping function which was ultimately developed to meet the design requirements described in Section 2.4. Discussion of specific technology incorporated into the machines is provided in the following paragraphs.

3.1 Robot Proper. The robots are of unique kinematic design, developed by Southwest Research Institute especially for manipulation of process equipment along fighter aircraft surfaces. Figure 12 includes nomenclature which will be used in the ensuing discussion.

Each robot consists of a base (referred to as the traveler) which incorporates the major electrical and control components, a column assembly, and an arm (the mechanical positioning device) with provision for mounting the end effector (the end of arm tooling for paint removal). The components are articulated so that the column will pivot outward and inward from the traveler in order to position the arm for access to a portion of the aircraft. This approach reduces the length of the robot arm required to reach all the surfaces of the subject F-16 fighter aircraft.

Each robot has a total of 9 degrees-of-freedom. These consist of two positioner axes, a 6 axis articulated arm, and a single tool roll. All nine axes use low backlash cycloidal drives (Dojen) powered by AC brushless servo motors (Moog), which is typical of the state of the art in robot joint drive technology. Multiple resolvers (Micron/Harowe) on each axis provide absolute position feedback and eliminate the need for homing of the robot. Electrical limit switches and motor thermal switches are incorporated on all axes. Robot payload is determined mainly by the torque limits of the wrist drive reducers but is nominally 100 pounds total (including end effector weight, blast hose weight, and blast reaction force; depending on loading configuration).

Axes 1 and 2 comprise the positioner. Axis 1 provides translation for the entire robot assembly on a floor-mounted track with a gear rack drive to position the pivoting column and 6-axis arm along the length of the track. The Axis 2 column pivot is used to position the column and 6-axis arm in and out from the robot traveler. If an aircraft is present in the facility during robot operations, the column pivot is used to move the column to the folded or "tucked" position against the traveler to allow passage of the robot by the wing tip of the aircraft. Control software is provided to allow coordinated movement of the two positioner axes to drive the column to a programmed X-Y position relative to the robot track.

A column foot and brake are used to stabilize the arm once Axes 1 and 2 have been positioned. The foot is mounted to the bottom of the column and incorporates an air cylinder which is used to apply a fixed load against the supporting floor. After the load is applied, the cylinder is mechanically locked in position so that it does not move even if air pressure is lost. Axis 2 includes a large disk brake at the top pivot joint which is used to lock the column into position. It operates as a standard disk brake and is energized by compressed air, once the column has been moved into position and stopped.

Axes 3 through 9 comprise the robot arm proper, providing the 6 degrees-of-freedom which are coordinated to provide translation and orientation of the tool center point. The column provides a base for the vertical motion and shoulder rotation of the arm. Axis 3 provides the column vertical drive, consisting of a chain hoist mechanism, including positive downward drive. Axis 4 provides the column shoulder rotation, consisting of a pinion gear driving a large gear integral to the upper ball bearing support for the axis. Axis 5 is the elbow of the 6-axis articulated arm, which uses a right angle drive to transfer power to a cycloidal reducer. Axes 6, 7, and 8 are the yaw, roll, and pitch of the arm wrist. The Axis 9 tool roll is used to change the end effector orientation to the surface, necessary to avoid "wrapping" of the heavy blast hoses.

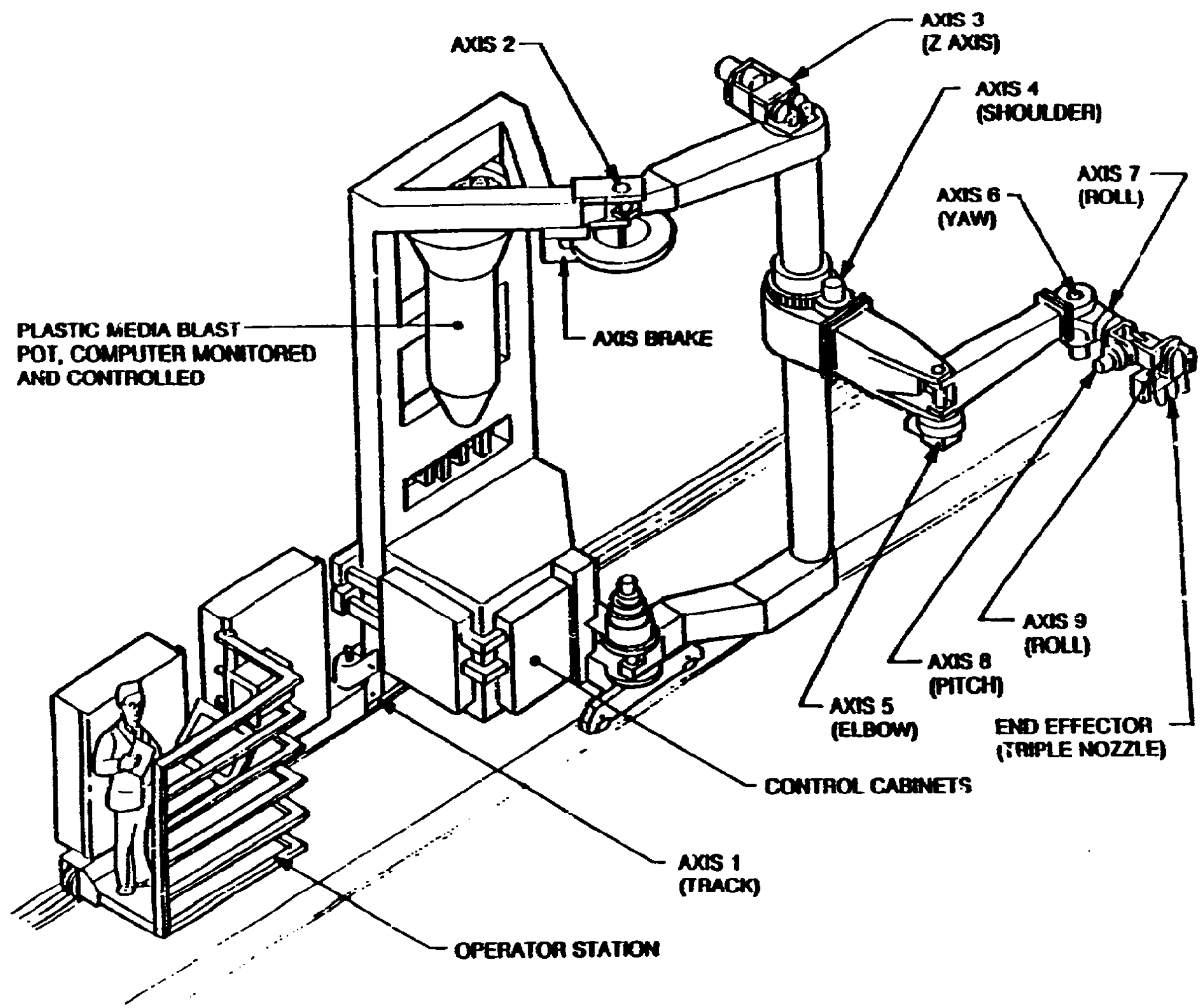


Figure 12. Robot Design Pictorial View

Coordination of the multiple axes is provided by a Modicon 5200 controller with Southwest Research Institute-developed software. This controller is of Multibus design and incorporates an 80286 processor for the main CPU board, a separate processor for programmable logic controller (PLC) input/output functions, and dedicated servo axis digital controllers for each pair of motor axes. This equates to a total of 7 processors in the 5200 controller for coordination of the robot motions and process functions. Modicon digital servo amplifiers are provided for each of the motor axes to provide an integrated control and drive system. The robot is capable of operating with end of arm speeds of up to 10 inches per second.

Teaching of the robot path files is accomplished by moving the robot to discrete points on the aircraft and recording these points. Points are recorded in a "list file" into which is also recorded "process records" so that the paint stripping application programs can be edited at the keyboard and stored on disk. Paths are programmed so that a "raster pattern" is followed to strip paint from a given surface area, and long strokes are generally favored to maximize the stripping time between transition moves. In order to facilitate the somewhat tedious teaching process, large flat areas can be programmed by teaching a total of 6 points to define the boundary of the surface and by using an auto-path-generating software function to create the discrete robot motion and process control functions. The aircraft is typically taught on a panel-by-panel basis so that the material type for each panel can be recorded with the list file, and process control information can be maintained in separate "global" files to describe the process parameters to be used on a particular type of material.

3.2 Blast Pot. A blast pot is carried on each robot to provide "local control" of the paint stripping process parameters of blast pressure and media flow rate. This local control becomes necessary because of the response lag that would be introduced if the blast pot and control equipment were located as stationary elements of the facility. The blast pot is connected by means of a hose to the media transport system, which is a dense phase transport system designed to maintain a minimum level of plastic media in the upper chamber of the blast pot. The blast pot is a continuous feed design and allows nonstop blasting with no blow down or refill cycles required, i.e. a two-chamber pot design is used to cycle the media from the upper chamber into a lower chamber, which must remain pressurized at the nominal blast pressure setting while stripping paint. The blast pot air is supplied by a single air supply hose routed with the robot umbilicals, and gravity feed is used to meter media to the three identical blast hose outlets through proportional valves. The blast pot is monitored and controlled by the robot controller PLC during all blasting operations. The PLC is used to provide analog control of blast pot air pressure and media mass flow to the three blast hoses.

3.3 End Effector. The end effector is the robot end of arm tooling which incorporates the components for directing and monitoring the plastic media blast. Three 1/2-inch bore nozzles direct the media blast, which are spaced to achieve the desired blast overlap for a nominal 18-inch surface standoff distance. The blasting process is not significantly affected for standoff distances in the range of 12 to 24 inches. Each nozzle incorporates a pressure transducer to verify blasting pressure at the nozzle in order to provide operator feedback for monitoring of correct process operation. A pair of infrared distance (range) sensors are mounted on the end effector to detect anomalous conditions where the end effector may be closer to the stripping surface than the programmed standoff distance. As a back-up collision detection system, a wire loop (not shown in the figure) is suspended around the periphery of the end effector and attached to wobble switches to detect unintended contact with an object prior to hitting the main structural elements of the end effector.

3.4 Paint Sensor System. The end effector paint sensor components include light emission and collection devices. Four standard halogen blasting lights are used to illuminate the painted surface and provide the light energy needed for collection and transmission to the paint sensor electronics. The receptors are six lens assemblies, each consisting of a simple flat viewing window and an internal focusing lens. Four of the lens assemblies are mounted in line with the three blast nozzles to view the blast footprint area, and two more are mounted ahead and behind to monitor the substrate condition before (lead sensor) and after (lag sensor) passage of the blast footprint. This arrangement of sensors is indicated in Figures 6 and 7. Collected light energy is focussed by the lens assemblies onto the end of a fiber optic cable which transmits the light to the paint sensor electronics housed in a remote enclosure on the robot. Air knives are used to keep the exposed optical elements clean.

Figure 13 indicates the spectral reflectance characteristics of typical paint and substrate materials, which provides the operating principle of the paint sensor. Reflected light energy in two infrared frequency bands is measured by means of silicon (800 nm) and germanium (1200 nm) detectors. Analog electronics for each of the six end effector light receptors provide amplification and ratioing of the two optical detector outputs which, after proper calibration of the system on sample panels, provides discrimination between a painted surface and a bare substrate material. By means of a specially developed software algorithm, a real-time "percent paint" signal is provided to the robot path velocity control loop which can then adjust the robot path speed based on the sensed conditions in the blast footprint. As a simplified explanation, paint sensor information is provided by "looking at" the centerline of the blast footprint and adjusting the robot velocity so that a nominal "50% paint remaining" signal is maintained, i.e., it is assumed that the "front half" of the blast footprint removes half of the paint and that the "back half" of the blast footprint removes the other half of the paint on the surface. Additional receptors are used for monitoring the condition of the surfaces ahead of and behind the blast footprint, and this information is incorporated into the robot velocity control algorithm.

3.5 Operator Interface. Operator control of the automated system is simplified by the integration of all functions through Southwest Research Institute-developed computer controls and software. Each robot includes its own control computer, a Modicon 5200, which the operator uses for teaching of new path programs; initializing the robots and teaching of aircraft reference points (to properly offset the robot path programs based on the actual location of the aircraft); and during software-aided maintenance operations. The two robot controllers (one for each of the robots) are coordinated by the cell controller which serves as the main operator interface during automated paint stripping operations.

The robot control station is located on the robot. Controls provided for operating the robot include the robot control monitor with keyboard, the teach pendant, and robot control video monitor. The robot control monitor consists of monochrome display and built-in membrane switch keyboard in a ruggedized enclosure. The various operating modes of the robot are selected through a menu driven interface displayed on this monitor to simplify operator interaction with the system and to provide software checking of input parameters. The teach pendant is used for manual operation of the robot arm to position the tool center point, primarily to teach reference points. As such, the teach pendant is provided with a long cord to allow the operator to move about in the robot work space to provide a clear view of operations. An emergency stop switch allows the operator to stop all robot motions as needed. Operation of the RPSC robot is similar to operation of any commercial robot, with the addition of special functions particular to the paint stripping operations. The robot control video monitor is connected to a camera mounted on the end effector to provide

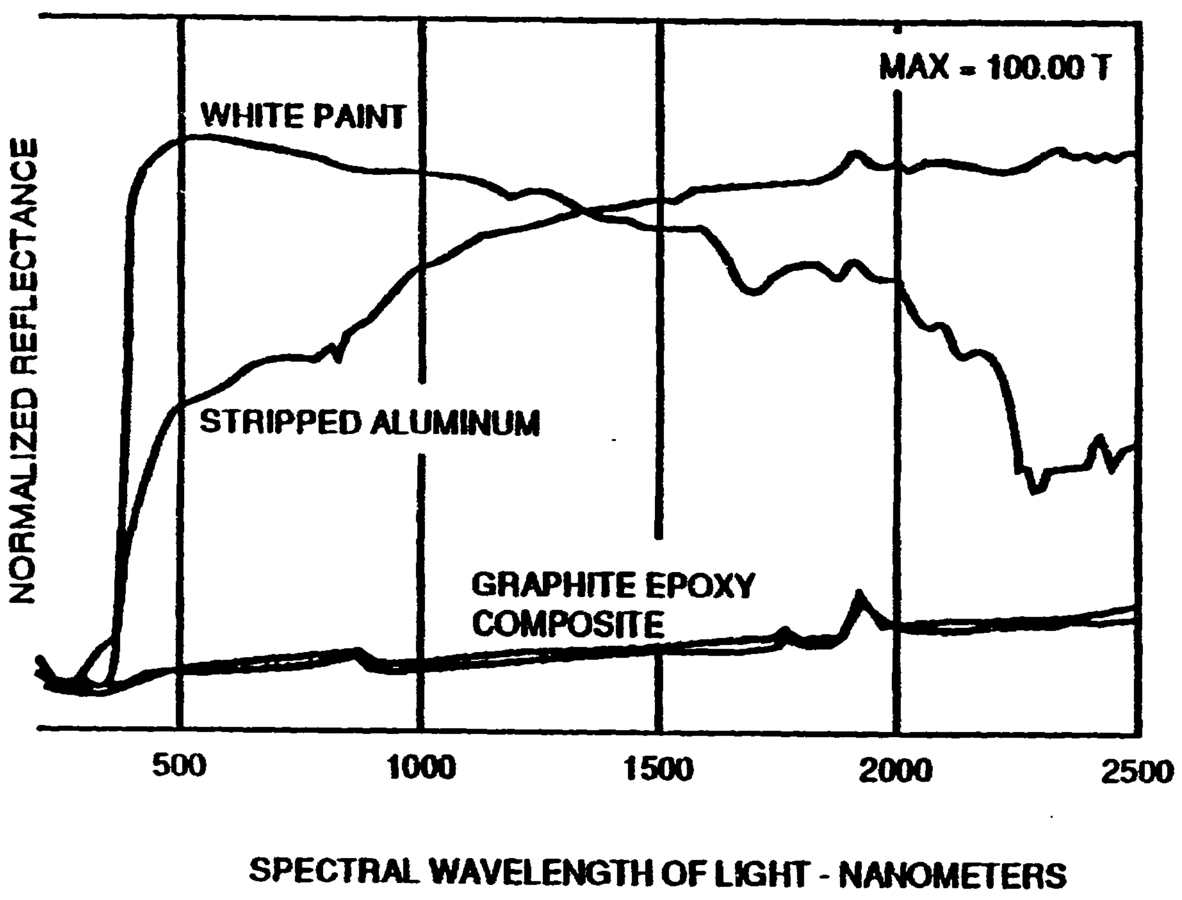


Figure 13. Paint Sensor and Process Control Concept

a close range view of the paint stripping operations as seen from the end effector. This video signal is also provided to the operator located at the remote observation and control station. The operator is required to use the robot control station only for initial set-up of the robots when a new aircraft is brought into the facility. All paint stripping operations are performed without personnel in the blast booth area.

The cell controller is located remotely in the control room to provide a safe vantage point for observation of automatic operations. Automatic paint stripping operations are initiated and controlled through the PC-based cell controller, which acts as the master of the system during automatic operation, monitoring, and coordinating the activity of the robots. It is in communication with each of the robot controllers to pass status and error checking information. Provision is made in the user interface software to select operation of one or both of the robots for cases where small aircraft components are to be automatically stripped. In addition, the cell controller provides for storage of the various aircraft robot path and process record files.

The cell controller operator interface includes a color monitor which provides graphical display of individual robot status and process control information. The operator initiates commands by selection of menu options using keyboard function keys. RPSC operation information and errors are recorded in a history file on the cell controller to document operator-entered data and paint stripping information for each shift of operation. A printer is provided for hard copy of such data.

Video monitors in the control room provide the operator additional views of the robot operations. These are connected to a video camera on each of the robot end effectors to provide an up-close view of the actual paint stripping progress at the nozzles. The operator can adjust by means of a potentiometer input the set point for the adaptive control loop based on their observation of the stripping results displayed on the video monitor for each robot. If desired by the operator, the robot path velocity can be adjusted manually based on visual feedback at these video monitors.

3.6 Operational Sequence

The hardware and software described in the previous report sections are integrated to provide automated paint stripping as directed by the operator through the cell controller. Robot path and process control programs are developed using semiautomated path teaching methods for each different component or aircraft to be stripped by the automated system. These program files are maintained on the cell controller for operator selection. The general sequence of events for automated paint stripping are as follows:

1. The aircraft must be prepared as required for the paint stripping process. For PMB, this requires masking and sealing to prevent media ingress.

2. The aircraft must be positioned in the paint stripping facility within prescribed tolerances and elevated on jack stands to the prescribed vertical position. The position of landing gear and aircraft control surfaces must match the condition during which the robot path program was taught.

3. The operator must teach predetermined reference points on the aircraft using each of the robots. This procedure is semiautomated by stepping through a robot path program which leaves the robot end effector positioned near, but not touching, the intended reference point.

4. The robot is moved under program control to a home position in preparation for paint stripping startup. Semiautomated calibration of the paint sensor system is completed.

5. After the robots are referenced to the aircraft, calibrated, and homed the operator returns to the control room and initiates the automated paint stripping through the cell controller interface.

6. The operator monitors the blasting process by monitoring the video displays and computer screen, and by observing progress through the control room observation window. The operator has the capability to pause, stop, or emergency stop the system during the blasting operations.

7. After stripping is completed, the aircraft is demasked.

Additional features are provided in the system to record system operation information and to facilitate maintenance troubleshooting. Software is password protected to limit access to specific features for properly qualified and trained personnel only.

3.7 Production Use of the Hill AFB RPSC

At the time of this report submittal, the RPSC has been used to strip approximately 40 F-16 aircraft of various models. Due to the wide range of paint conditions that can be encountered (age, thickness, adhesion, primer type, etc.), strip rates can vary greatly, but a "robot-on time" of 8 to 12 hours for each aircraft is typically experienced. At least 95 percent of the F-16 surface area can be stripped with the robot pair, where accessibility is restricted primarily around the forward engine intake duct and the tail hook areas. Figures 14, 15, ans 16 provide "before" and "after" photos of stripped F-16 aircraft surfaces to indicate stripping coverage, although the photograph reproductions do not lend themselves to detailed inspection of stripping quality.

Based on input from the system operators, the controls for adjustment of the automatic paint sensor control loop set point or manual robot speed were moved to a more convenient "table top" arrangement. The operators report that control adjustments during stripping are effective for reducing the amount of manual touch-up required after the automated stripping. In addition to providing controlled, consistent stripping, the six-nozzle robotic PMB process requires only two operators instead of the previous six-person crew using four nozzles, thus, reducing labor costs and aircraft flow time.

Figure 14a. F-16 Aircraft Surfaces Before Automated Stripping

Figure 14b. F-16 Aircraft Surfaces After Automated Stripping

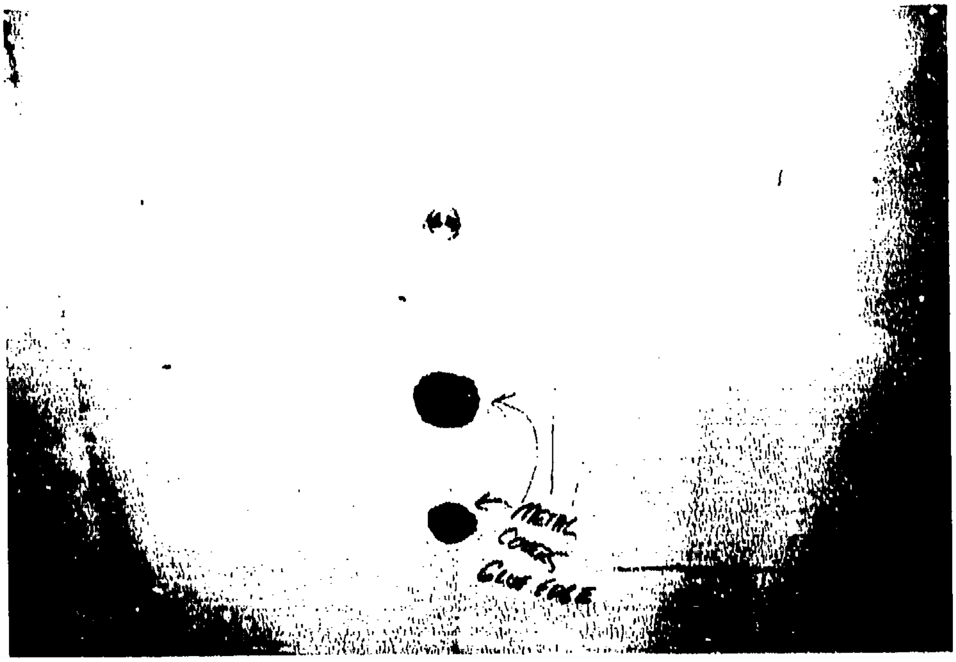


Figure 15a. F-16 Aircraft Surfaces Before Automated Stripping

Figure 15b. F-16 Aircraft Surfaces After Automated Stripping

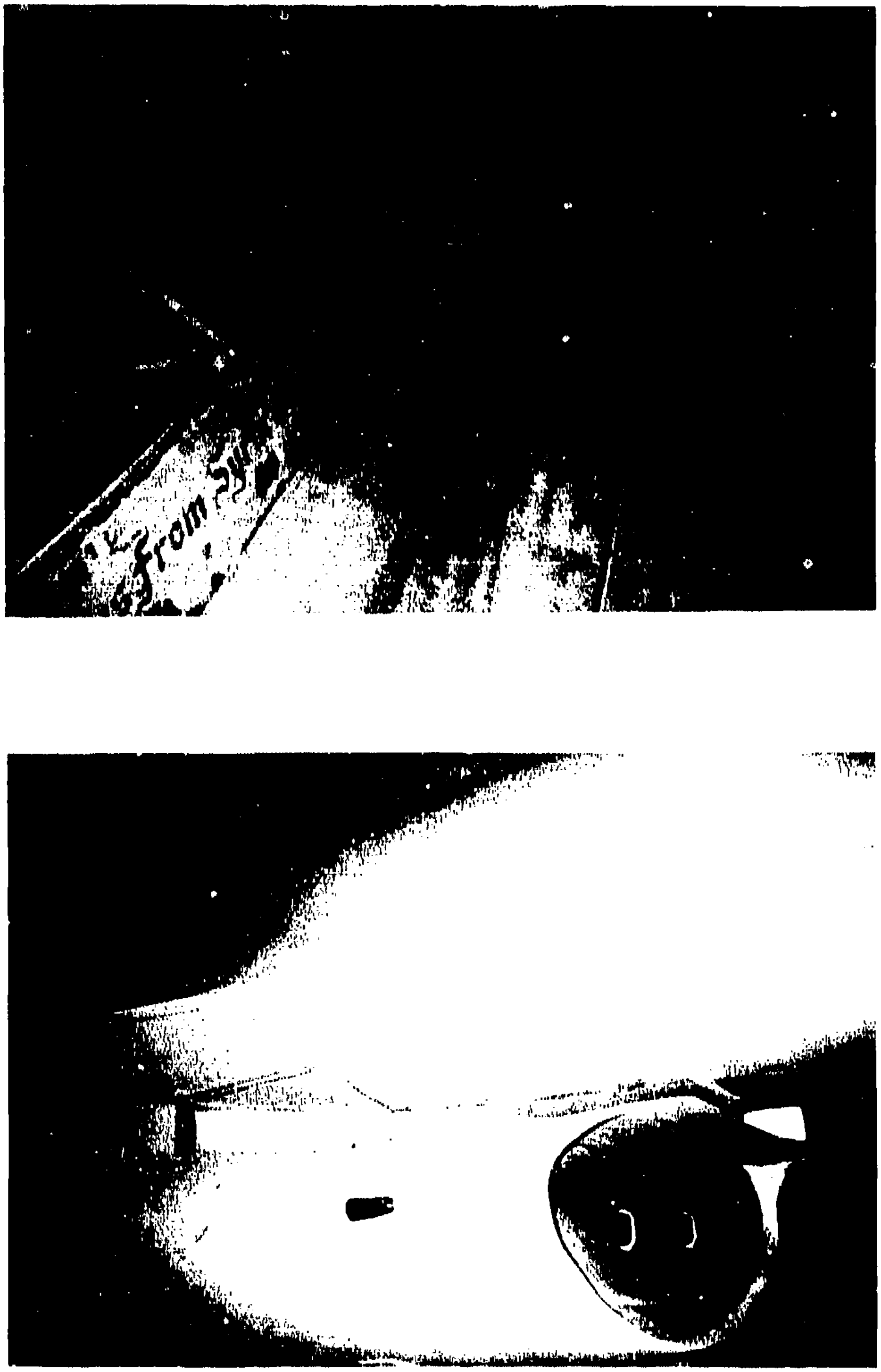


Figure 16. F-16 After Robotic PMB Paint Stripping

APPENDIX A

MATERIALS TEST PLAN

GENERAL TEST PLAN AND PROCEDURES FOR ROBOTIC PAINT STRIPPER CELL (RPSC)

Contract No. F33615-86-C-5044
Item No. 002
Sequence No. 21

SwRI Project 05-1078

December 8, 1986

GENERAL TEST PLAN AND PROCEDURES FOR
ROBOTIC PAINT STRIPPER CELL (RPSC)

Contract No. F33615-86-C-5044, SwRI Project No. 14-1078
Item No. 002, Sequence No. 21

1.0 PURPOSE

The overall purpose of the RPSC General Test Plan and Procedures is to assess the technical capabilities of non-chemical processes for removing organic coatings from exterior aircraft surfaces. We have restricted this assessment to three non-chemical processes which have shown prior feasibility for removing organic coatings from aircraft - plastic media, lasers, and carbon dioxide "dry ice." The Test Plan itself has been designed to generate data on the capabilities and effects of the laser method and the dry ice blast method, leading to a three-way comparison with previously-generated plastic media blast data.

2.0 PREVIOUS DATA

Plastic media paint stripping has been under investigation since at least 1978. Laser paint stripping has been investigated since at least 1981, and dry ice paint stripping since 1984. Numerous reports, studies, and tests have been written or performed on plastic media, a few on lasers, and very few on dry ice. Table 1 identifies those criteria where statistically confirmed data already exists. Plastic media is the only method of these three that is approved for aircraft paint stripping. That approval applies to the F-4 aircraft at depot level maintenance. The authority is granted by Air Force Technical Order 1F-4C-3-1-6. In addition, A.F.T.O. 1-1-8 approves of abrasive blasting under limited conditions. Air Force Technical Order 1-1-2 states that abrasive blasting "provides an excellent surface finish for primer adhesion."[1] Concerning mechanical properties, A.F.T.O. 1-1-2 has the following to say:

> The impingement of the beads on the sound base metal creates a thin layer of metal with residual compressive stresses which make this surface more corrosion and fatigue resistant than the base metal.

3.0 CRITERIA

The Process Selection Test Plan will directly address several criteria in the assessment of laser and dry ice paint stripping (see Table 2). In addition, several criteria will be addressed indirectly as an outgrowth or consequence of the Test Plan. Some of these criteria can only be addressed qualitatively or speculatively. A few criteria will be investigated through in-house computer modeling and/or physical modeling. Applied Concepts Corporation is performing an economic analysis which will deal with several economically-related criteria. Finally, there are several

criteria which are presently being addressed by other contractors in concurrent DoD contracts.

4.0 MATERIALS TO BE TESTED

See Figure 1 "Robotic Paint Stripper Cell (RPSC) Process Selection Test Plan."

The materials included in this test plan are as follows:

A. ALUMINUM SHEET METAL PANELS

1. Alclad 7075-T6 aluminum, thicknesses: .032", .071", and .160".

2. Anodized 7075-T6 aluminum

   a) Thicknesses: .032", .071", and .160"
   b) Treatment: Sulfuric acid anodized and dichromate sealed.

3. Alclad 2024-T3 aluminum, thicknesses: .032", .071", and .160".
4. Anodized 2024-T3 aluminum

   a) Thicknesses: .032", .071", and .160"
   b) Treatment: Sulfuric acid anodized and dichromate sealed.

Sheets of aluminum described above will be provided in the dimensions and quantities set forth in Table 3. This will include cutting larger sheets down to 48" x 48" sheets, and anodizing those aluminum sheets as so indicated (see Figures 2a, 2b).

In addition, all 48" x 48" aluminum sheets will be cut into smaller panels, 12" x 16" or 16" x 16", as set forth in Table 4. All panels will be drilled and metal-tagged with appropriate serial numbers.

B. THIN SKIN ALUMINUM STRUCTURES

1. Thin Skin Aluminum Honeycomb Structure

   (a) Face Sheets - 0.016 inch thick 7075-T6 alclad aluminum alloy

   (b) Face sheet preparation for bonding

      (1) chromic acid anodized
      (2) coated on unclad side with BR-127 bonding primer

   (c) Honeycomb core material - 5052 aluminum

   (d) Honeycomb core thickness - 0.5 in.

   (e) Honeycomb core density - 2.3 lb/cu ft.

   (f) Bonding adhesive - Hysol epoxy EA9601.2, weight .045 lbs/sq ft.

One 48" x 48" honeycomb structure will be fabricated using the Hysol adhesive indicated above and applied in accordance with Hysol recommended procedures. Curing will be performed according to Hysol adhesive requirements. Upon completion of curing cycle, 48" x 48" structure shall be divided into twenty-four (24) 8" x 12" panels (see Figure 5). All panels shall be drilled and metal-tagged with appropriate serial numbers.

2. Thin Skin Aluminum Metal to Metal Bonded Structure

   (a) Aluminum material - 0.016 in. 7075-T6 alclad aluminum alloy

   (b) Bonding preparation

      (1) chromic acid anodizing
      (2) coated on unclad side with BR-127 bonding primer.

   (c) Bonding adhesive - Hysol epoxy EA 9601.2, weight .045 lbs/sq ft.

Two (2) 48" x 28" metal-to-metal bonded structures will be fabricated. Each structure will consist of two (2) sheets of thin skin aluminum (described above) bonded together with Hysol epoxy adhesive in accordance with Hysol recommended procedures. The location of the bonded region shall be in accordance with Figure 6. Curing will be performed according to Hysol adhesive requirements. Upon completion of curing cycle, each 48" x 28" structure will be divided into sixteen (16) 6" x 14" panels as indicated in Figure 6. All panels will be drilled and metal-tagged with appropriate serial numbers.

C. GRAPHITE/EPOXY COMPOSITE PANELS

1. Material - Hercules AS4 fiber and 3501.6 resin.

2.

<u>Thicknesses</u>	<u>Fiber Orientation</u>
8-ply	[±45, 90, 0]s*
12-ply	[±45, 0, 0, 90, 0]s
80-ply	[±45, 0, 0, 90, 0, ±45, 90, 0]s (4 times)

Graphite/epoxy composite panels will be fabricated with the materials listed above in the dimensions and quantities listed in Table 3. In addition, large (24" x 24") fabricated panels shall be cut up into smaller 6" x 6" panels as set forth in Table 4. All panels will be drilled and metal-tagged with appropriate serial numbers.

*s - means symmetrical

5.0 TEST PANEL QUALITY ASSURANCE

Refer to Tables 3, 4, 5 and 1 for the following descriptions.

5.1 Aluminum Panels

5.1.1 Baseline fatigue life and crack growth rate will be determined on all alclad and anodized baseline fatigue and crack growth rate specimens per Table 5.

5.1.2 All anodized test panels which are subject to four paint/strip cycles will have electrical surface conductivity tests accomplished initially to determine the presence of an anodize coating (see Table 6). These anodized test panels will also be surface conductivity tested after each paint removal.

5.1.3 Surface roughness (in microinches) will be measured on all aluminum sheet, honeycomb, and bonded test panels which are subject to four paint/strip cycles (see Table 6). Measurements will be made prior to the first paint coating and after each paint stripping.

5.1.4 All aluminum honeycomb structures and thin sheet bonded structures designated as "Baseline Panels" or "Test Panels" will be ultrasonically inspected initially to ensure the absence of debonded areas or voids in the adhesively bonded structure (see Table 6). These bonded panels will also be ultrasonically inspected after each paint removal process to determine whether debonding has occurred as a result of the paint stripping process.

5.1.5 Baseline adhesive bond strength will be determined on baseline T-peel bond strength test specimens per Table 6.

5.1.6 All thin sheet metal-to-metal bonded aluminum test panels will be visually inspected for warpage resulting from paint stripping.

5.2 Graphite/Epoxy Composite Panels

5.2.1 All graphite/epoxy composite baseline and test panels will be initially ultrasonically inspected to insure the absence of debonded areas or other abnormalities in the bonded structure. All test panels will be ultrasonically inspected after each paint removal process to ensure that no ply debonding or matrix cracking had occurred as a result of the paint stripping (see Table 6).

5.2.2 Test panels will be x-rayed if any macro areas of fiber breakage or internal matrix damage has been detected by ultrasonic inspection.

5.2.3 Physical property data and baseline four point flexural strength will be determined on baseline panels per Table 1.

5.2.4 Surface roughness (in microinches) will be measured on all graphite/epoxy composite test panels subject to four paint/strip cycles (see Table 6). Measurements will be made prior to the first paint coating and after each paint stripping.

6.0 TEST PANEL PREPARATION FOR PAINT REMOVAL PROCESS

6.1 Pre-treatment, Coating and Curing of Aluminum Test and Practice Panels.

The following applies to 7075-T6 and 2024-T3 aluminum alclad panels and aluminum anodized panels.

6.1.1 The panels will be alkaline detergent cleaned using MIL-C-25769 material.

6.1.2 The panels will be deoxidized using material conforming to MIL-C-38334.

6.1.3 The panels will be chemical conversion coated using material conforming to MIL-C-81706 and applied in accordance with MIL-C-5541.

6.1.4 The panels will be primer coated to a dry film thickness of 0.0006 to 0.0009 inch with epoxy primer conforming to MIL-P-23377.

6.1.5 The panels will be topcoated to a dry film thickness of 0.0017 to 0.0023 inch with polyurethane paint conforming to MIL-C-83286B.

6.1.6 The panels will be cured at ambient conditions of 75°F. and 50 ±5% RH for seven (7) days.

6.1.7 After seven (7) days of ambient cure, the panels will be baked at 210°F ±2 for 96 hours.

6.2 Coating and Curing of Graphite/Epoxy Composite Panels

The following applies to graphite/epoxy composite test and practice panels (see Table 7 for panel painting schedule):

6.2.1 The peel ply will be removed.

6.2.2 The panels will be immediately primer coated to a dry film thickness of 0.0006 to 0.0009 inch with epoxy primer conforming to MIL-P-23377.

6.2.3 The panels will be topcoated to a dry film thickness of 0.0017 to 0.0023 inch with polyurethane paint conforming to MIL-C-83286B.

6.2.4 The panels will be cured for seven (7) days at ambient conditions of 75°F ±2 and 50 ±5% RH.

6.2.5 After ambient conditioning, the panels will be cured at 210°F ±2 for 96 hours.

7.0 EQUIPMENT AND PROCEDURES USED FOR PAINT REMOVAL

All materials tested will be subject to four paint/strip cycles in accordance with Figure 1. If, however, it is found that any paint stripping method as employed in this program or with any reasonable extension of the technology is incapable of removing paint from any particular material in this test plan, or if any other "show-stopper" exists which would prevent that paint stripping method from being implemented into a Robotic Paint Stripping Cell, then the paint/strip/test cycles will be terminated at that point for that paint strip process on that particular material.

7.1 Laser Paint Stripping

Laser paint stripping will be performed in accordance with Table 8a by an independent contractor within the laser industry. The equipment used for laser paint stripping will be a standard commercially available CO_2 laser. The most desirable configuration would include feedback and control instrumentation linked to a laser beam delivery system. If this is not possible, the contractor will perform the tests using his available equipment that most closely approximates a production paint stripping system. The contractor shall describe, within the limits of propriety, the system actually used for tests and shall provide preliminary estimates of the additional equipment needed to produce a production system. The time required to remove the paint from each sample will be recorded. The contractor will provide estimated extrapolations of the removal rates and operating costs ($\$/ft^2$) that would be realized by a production system together with the basis for the estimates.

Contractor shall strip to the best of his ability with available equipment aluminum and composite panels provided by Grumman and SwRI (see Table 8a). Contractor shall adjust parameters (e.g. power and travel speed) so as to optimize efficiency of paint removal without any visible, apparent damage to substrate. These optimally laser-stripped panels are listed in Table 8a under the heading of "optimal" for each paint/strip cycle. In addition, contractor shall strip another set of panels at 20% overexposure. These panels are under the heading "overexposed."

7.2 CO_2 Dry Ice Paint Stripping

The CO_2 "dry ice" paint removal process will be performed in accordance with Table 8b by an independent contractor within the CO_2

dry ice blasting industry. Contractor shall strip to the best of his ability with his available equipment, aluminum and composite test panels provided (see Table 8b). Nozzle angle, stand-off distance, air pressure and travel rate will be optimized in trial runs prior to actual test runs. The time required to remove the paint from each sample will be recorded. The contractor will provide estimated extrapolations of the removal rates and operational costs ($/ft^2) that would be realized by a production system together with the basis for the estimates.

7.3 Practice Paint Stripping

Practice panels shall be made available by Grumman in accordance with Table 4 for the purpose of paint stripping optimization and practice. The actual distribution of these practice panels between laser paint stripper and dry ice paint stripper will be worked out at a later date.

8.0 TEST PROCEDURES

See Table 9 for test standards and specimen sizes.

8.1 Surface Roughness Measurements

8.1.1 Scope

Surface roughness of exterior aircraft structure caused by sanding, abrasive blasting using various types of abrasive media or other means of mechanically abrading the surface can result in several unsatisfactory performance phenomena. Some of these include increased aerodynamic drag, fatigue crack originators, increased fatigue crack growth rates, and potential increased corrosion rates. This section contains the general requirements for evaluating the effects of paint removal on the surface roughness of aluminum and graphite/epoxy composite structures.

8.1.2 Applicable Documents

None.

8.1.3 General Requirements

Surface roughness will be measured by a recording profilometer capable of reading a maximum centerline, average roughness value (Ra) of 0.010 in. and a maximum peak-to-valley value of 0.030 in. Minimum Ra values detectable will be less than one microinch (0.000001 in.). The strip-chart recorder used with this profilometer will produce a permanent record of surface contours. Surface roughness measurements will be taken on aluminum alclad and anodized panels and on graphite/epoxy composite panels indicated in Sections 5.1.3 and 5.2.4. Each data point will represent an average of ten (10) readings (in microinches)

taken every 0.03 inches over 0.30 inches travel of the probe. Five (5) data points will be gathered from each panel.

8.2 Surface Electrical Conductivity

8.2.1 Scope

This procedure provides the general requirements to determine if anodize coatings have been removed from aluminum alloys using the surface electrical conductivity technique. Surface electrical conductivity measurements will be made on all anodized aluminum panels indicated in Table 6 to determine the presence of anodize coating. Preliminary conductivity measurements made prior to paint removal will be compared with measurements made after paint removal.

8.2.2 Applicable Documents

None.

8.2.3 General Requirements

8.2.3.1 Discussion

Anodize coatings, chromic and sulfuric, are applied to aircraft aluminum structure for increased long-term protection against corrosion. Properly applied undamaged anodize coatings are electrically nonconductive. Therefore, the procedure for determining if an anodize coating has been damaged during refinishing processes is to use a volt/ohm meter to determine if electrical conductivity is present in areas of the anodized structure. This procedure assumes that the anodize coating was undamaged prior to paint removal from the aircraft either by sanding, plastic bead blasting or with chemical strippers.

8.2.3.2 The test procedure is as follows:

(1) Using 300 grit sand paper, lightly remove a small area, not to exceed one square inch of the anodize coating.

(2) Position both electrodes of the volt/ohm meter in the sanded area to ensure electrical conductivity.

(3) Maintain contact of the positive electrode with the sanded area and slowly move the negative electrode over the area to be inspected for damaged anodize coating.

(4) Any deflection of the volt/ohm meter indicator shows areas with the absence of the anodize coating.

8.3 <u>Fatigue</u>

8.3.1 Scope

8.3.1.1 This section contains the general requirements chosenfor evaluating the effects of paint removal on the fatigue properties of metallic materials. (See Figure 3 "Flowchart for Fatigue Test Specimens").

8.3.2 Applicable Documents.

8.3.2.1 <u>Definitions of Terms Relating to:</u>

ASTM E 206	Fatigue Testing and the Statistical Analysis of Fatigue Data

8.3.2.2 <u>Method/Practice:</u>

ASTM E 466	Conducting Constant Amplitude Axial Fatigue Tests of Metallic Materials
ASTM E 468	Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials
ASTM E 467	Verification of Constant Amplitude Dynamic Loads in an Axial Load Fatigue Testing Machine
ASTM E 739	Statistical Analysis of Linear or Linearized Stress - Life (S-N) and Strain Life (E-N) Fatigue Data
MIL-HDBK-5C	Chapter 9, Section 9.6, Subsection 9.6.2, Tests of Significance

8.3.3 General Requirements

8.3.3.1 <u>Discussion</u>

Fatigue is a failure mode that is composed of two stages; crack nucleation and crack propagation. Crack nucleation usually occurs at some imperfections or discontinuities in a material such as inclusions, machining scratches, fastener holes, etc. Crack propagation in normal material is dependent on the average properties of a material with localized imperfections playing a secondary role in the process. It is possible that laser and dry ice paint removal could potentially have a significant effect on fatigue data inasmuch as crack nucleation sites may be introduced on the surface of the material by the cleaning process. Of all mechanical properties, fatigue will potentially be affected the most.

8.3.3.2 Requirements

(1) Planning. Baseline specimens will be tested at two (2) stress levels, i.e., one stress that will produce fatigue life at about 100,000 cycles and the other stress that will produce a fatigue life at about 500,000 cycles. Tests which run beyond 500,000 will be cut off at 5,000,000 cycles. At each of the stress levels, five (5) baseline fatigue tests will be performed on unpainted, unstripped material. After each 8" x 12" test panel has been painted and stripped the appropriate number of times, it, too, will be cut into five fatigue test specimens. Fifty percent of these panels will be tested at the higher stress and fifty percent will be tested at the lower stress.

(2) Specimen Design and Preparation. Test specimens will be designed and prepared according to ASTM Standard Practice E 466. Five (5) fatigue specimens will be made from each 8" x 12" aluminum test and baseline subpanel. Test specimen size will be 7" x 1" using the tangentially blended fillets as shown in Figure 3 of E 466. Specimen preparation will be done with great care to avoid undercutting at the fillets, introducing residual stresses, or having stress risers along the machined edges. All specimens will be inspected using 20X or greater magnification. All transverse marks, cracks, or excess material, such as burrs along the machined edges, will be removed.

(3) Testing. The fatigue tests will be conducted at room temperature in accordance with ASTM Standard Practice E 466 and preferably using electrohydraulic servo-controlled testing machines. The tests will be performed using axial tension-tension type of loading. The following stress ratios (min stress/max stress = R) will be used:

(a) R = 0.3 for sheet material having a thickness less than 0.050 inch.

(b) R = 0.1 for sheet material with a thickness greater than 0.050 inch.

(4) Test Results and Analysis. The fatigue data will be reported as given in ASTM Standard Practice E 468. If five (5) valid test data are available at a single stress level for both baseline and the paint removal conditions, then a statistical t-test will be conducted to test for a significant difference between the two sample means. Logarithms of the specimen lives will be used since it is common practice to assume that the logarithms of the fatigue lives belong to a normal distribution. See Subsection 9.6.2 in MIL-HDBK-5C.

8.4 Metallography

8.4.1 Scope

This procedure contains the general requirements chosen for evaluating metallographically the effects of laser and CO_2 dry ice paint removal on aluminum structures.

8.4.2 Applicable Documents

ASTM E 7	Metallography, Definitions of terms relating to.
ASTM E 2	Methods for Preparation of Micrographs of Metals and Alloys (Including Recommended Practice for Photography as Applied to Metallography).
ASTM E 3	Methods for Preparation of Metallographic Specimens.
ASTM E 340	Methods for Macroetching Metals and Alloys.
ASTM E 407	Methods for Microetching Metals and Alloys.

8.4.3 General Requirements

8.4.3.1 Discussion.

Metallography allows material evaluators to relate the constitution and structure of metals and metal alloys to their properties. When properly employed, metallography can prove useful in evaluating the effects of laser and dry ice paint removal on metallic structures. In particular, metallography can reveal the 2-D surface features created by paint removal; scanning electron microscopy can reveal the 3-D features. By using these techniques, the effects of paint removal can be assessed.

8.4.3.2 Requirements.

(1) Specimen Selection. Accurate selection of the metallographic specimen is probably the most important step in evaluating the effects of lasers and dry ice metallographically. The specimen must represent the material and process being studied. Generally, the specimen selected is a transverse cross-section which will best reveal variations in structure from center to surface; thickness and structure of protective coatings; depth and type of surface anomalies; and any other feature created by paint removal. The specimen size shall be amenable to mounting and preparation techniques.

(2) Specimen Sectioning. Specimens shall be sectioned such that the structure to be studied is not damaged during sectioning. Lubricants and cooling media typically prevent microstructural or physical damage from occurring during sectioning.

(3) Specimen Mounting. Cross-sections shall be carefully mounted to reveal as much detail as possible. Soft alloy surfaces can be plated before mounting or hard mounting material can be employed to prevent smearing of the edges during subsequent grinding and polishing operations.

(4) Grinding and Polishing Operations. These operations are well standardized and shall be adhered to.

(5) Etching Operations. These operations are also well documented and shall be matched to the material under study.

(6) Specimen Evaluation. Light or scanning electron microscopy can be used for evaluating the effects of paint removal, particularly the surface effects. Photomicrographs shall be taken of areas which are typical and which best illustrate the effects of paint removal.

8.5 Fractography

8.5.1 Scope

This brief contains the general requirements chosen for evaluating the effects of laser and CO_2 dry ice paint removal by using fractographic evaluation techniques.

8.5.2 Applicable Documents

Publications

MCIC-HB-06	SEM/TEM Fractography Handbook
MCIC-HB-08	Electron Fractography Handbook

8.5.3 General Requirements

8.5.3.1 Discussion

Fractography (light or electron) is a valuable technique for determining whether or not a paint removal process is the cause of a failure of metallic structures. Fractography, in conjunction with metallography and other evaluation techniques, can assist in assessing the effects of paint removal.

8.5.3.2 Requirements

8.5.3.2.1 Specimen Selection

All of the fractured fatigue specimens will be subjected to light optical fractography to determine the approximate location of the fracture initiation site. If the initiation site is not at the edge or corner of the specimen, then the specimen will be considered for electron fractography. Typically, all of the premature failures will be scrutinized in the scanning electron microscope while only some of the baseline specimen failures will be examined. The goals of fractography are first, to determine where the fracture initiated and second, to determine if the paint removal process was responsible for initiating the crack.

Accurate specimen selection is necessary for correlating the effects of paint removal to the properties of the material subjected to it. In selecting the specimen, the critical feature is the crack initiation site. Once the initiation site is located, it can be determined if the paint removal process was responsible. Therefore, it is critical that the specimen selected include initiation sites on the stripped surface.

8.5.3.2.2 Specimen Selection and Preparation

Once the specimen for study is selected, it shall be carefully sectioned so as not to damage the surfaces in question.

8.5.3.2.3 Specimen Evaluation

The critical features sought after using fractography include fatigue failure initiation sites, protective coating integrity, and surface finishes. By using a variety of techniques, it will be possible to determine if the paint removal process degraded or upgraded the substrate. Although the evaluation is subject to interpretation, several observations are required to conclusively determine the effects of paint removal on material properties using fractography.

8.6 Crack Growth Rate

8.6.1 Scope

This section contains the general requirements for evaluating the effects of paint removal on the crack growth rate of aluminum alclad and anodized panels. (See Figure 4 "Flowchart for Fatigue Crack Growth Rate Specimens".)

8.6.2 Applicable Documents

ASTM E 647-83

8.6.3 General Requirements

8.6.3.1 Discussion

Fatigue crack growth rate information obtained from tests on specimens is used to predict the growth of cracks in structures. A change in the growth rate in specimens will translate to a similar change in the growth rate of a crack in a component. Some paint removal processes appear to cause a peening effect on aircraft structural alloys. Peening causes a compressive residual stress on the surface and a tensile residual stress in subsurface material. This residual tensile stress will adversely change the stress ratio in the core material which in turn will accelerate the fatigue crack growth rate once a crack initiation has occurred. This test will determine the effect of laser and dry ice paint stripping on fatigue crack growth rates and provide a means of comparing against similar data generated on plastic bead paint removal.

8.6.3.2 General Requirements

(1) Requirements

The general requirements of this test are:

(a) Design and fabricate center crack tension (CCT) specimens to cover the range of K=7 to 15 KSI IN.

(b) Perform fatigue crack growth tests

(c) Accomplish data analysis to compare the crack growth rate of paint stripped specimens to that of baseline specimens.

(2) Specimen Design and Preparation

To accurately assess the effects of laser and dry ice paint stripping, tests on virgin and paint stripped panels will be run in a side-by-side comparison. All specimens of the same material will be removed from the same original sheet and will be tested to one set of parameters (stress ratio, frequency, environment, and machine). The quantity of specimens fabricated and tested for each thickness is shown in Table 1. Specimens will conform to ASTM 647 requirements.

(3) For each specimen, sufficient raw data (crack length and cycle count) will be obtained to develop an accurate description of the fatigue crack growth rate (da/dn) over at least one decade on the growth rate axis, and more if possible. There will be at least ten (10) points within a decade. For ease of data generation, the lowest growth rate will not be less than 10^{-8} in/cycle.

(4) Test Results and Analysis

Test results shall be analyzed in accordance with ASTM E 647 standard practices to determine da/dn vs K for each specimen. Each of the two cracks in the center cracked specimen are dependent and will be analyzed together. The K test range shall be divided into ten (10) equal increments and calculated values of da/dn for each of these increments determined for each test specimen using least squares curve fitting methods and the PARIS power equation. The equations may be segmented over the range of K if necessary to more accurately represent the test data. This discrete data at each K interval shall then be tested using a statistical T test for a significant difference between the means of virgin and plastic bead blasted samples. The data from like specimens is also to be combined and the median curve determined by best fit methods. The median curves may also be segmented if necessary. The median da/dn vs K equations are to be used to calculate and plot a vs n curves for comparison of virgin and plastic bead blasted material.

8.7 Adhesive Bond Strength of Aluminum Thin Sheet Metal-to-Metal Bonded Panels (T-PEEL TEST)

8.7.1 Scope

This section contains the general requirements for evaluating the effects of paint removal on the adhesive bond strength of aluminum thin sheet metal-to-metal bonded panels. (See Figure 6 "Flowchart for Thin Sheet Metal-to-Metal Bonded Structures" and Figure 7 "Thin Sheet Metal-to-Metal Bonded Aluminum Structure".)

8.7.2 Applicable Documents

ASTM D1876-72	Peel Resistance of Adhesives (T-Peel Test)

8.7.3 General Requirements

This method is primarily intended for determining the relative peel resistance of adhesive bonds between flexible adherends (in this case .016" aluminum) by means of a T-type specimen (see Figures 6 and 7). The bonded panels, 6" x 14", will be constructed in accordance with ASTM D1876-72. Each panel will be painted and stripped according to the schedule in Tables 7, 8a, and 8b. The one-inch grip section at the ends of each panel will be used to hold the panel in place during paint stripping. When each panel has been stripped for the last time, these grip sections will be removed and the panel will be divided into

five (5) 12" x 1" T-peel test specimens as shown in Figure 6.

8.8 Four-Point Flexure

8.8.1 Scope

This section contains the general requirements for evaluating the effects of paint removal on the four-point flexural strength of graphite/epoxy composite structures. (See Figure 8 "Flowchart for Graphite/Epoxy Composite Specimens".)

8.8.2 Applicable Documents

ASTM D790-84a, Method II

8.8.3 General Requirements

8.8.3.1 Test Panel Preparation and Geometry

Four (4) 24" x 24" graphite/epoxy composite structures made with AS4/3501-6 graphite/epoxy prepreg tapes will be fabricate. Each structure will be divided into sixteen (16) 6" x 6" panels prior to painting and paint stripping. Each baseline and test panel will be divided into five (5) 3" x 1" four-point flexure test specimens (see Figure 8). Thirty-three panels will be used for spares and practice.

8.8.3.2 Test Procedures

The load fixture shall be adjusted to a 2.0 inch span which results in a span-to-depth ratio of 32:1. Mid-span deflection in the flexure specimens shall be determined using a deflectometer. If the test specimens have deflections greater than ten percent of the span, the maximum stress will be calculated using the formula given in ASTM D790-84a.

PROCESS SELECTION TEST PLAN
PAINT/STRIP/TEST SCHEDULE

7075-T6 ALUMINUM	2024-T3 ALUMINUM	ALUMINUM HONEYCOMB	THIN SHEET BONDED STRUCTURE	GRAPHITE/EPOXY COMPOSITE
ALCLAD ANODIZED .032",.071",.160"				8 PLY 12 PLY 80 PLY
BASELINE TESTS				
SURFACE ROUGHNESS MEASUREMENTS SURFACE CONDUCTIVITY TESTS FATIGUE TESTS CRACK GROWTH RATE TESTS		SURFACE ROUGHNESS MEASUREMENTS ULTRASONIC INSPECTION	T-PEEL BOND STRENGTH TESTS SURFACE ROUGHNESS MEASUREMENTS ULTRASONIC INSPECTION	ULTRASONIC INSPECTION SURFACE ROUGHNESS MEASUREMENTS FOUR-POINT FLEXURE TESTS

FIRST PAINT COATING

FIRST PAINT STRIPPING

LASER	LASER	LASER	LASER	LASER
DRY ICE	DRY ICE	DRY ICE	DRY ICE	DRY ICE

FIRST CYCLE TESTS

(SAME AS BASELINE TESTS)

SECOND PAINT COATING

SECOND PAINT STRIPPING

(SAME AS FIRST PAINT STRIPPING)

SECOND CYCLE TESTS

THIRD PAINT COATING

THIRD PAINT STRIPPING

THIRD CYCLE TESTS

FOURTH PAINT COATING

FOURTH PAINT STRIPPING

FOURTH CYCLE TESTS

FIGURE 1

REFERENCES

1. "Corrosion Prevention and Control for Aerospace Equipment," T.O. 1-1-2 (Robins AFB, GA: Warner-Robins ALC/MMEDT, 1984), pp. 5-8.

2. Ibid., pp. 5-8.

REFERENCES

[1]Sidney Childers, et al, Evaluation of the Effects of a Plastic Bead Paint Removal Process on Properties of Aircraft Structural Materials (Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, OH, 1985).

[2]Application of Organic Coatings, T.O. 1-1-8 (Robins AFB, GA: Warner Robins ALC/MMEDT, 1985), pp. 2-8B.

[3]Corrosion Prevention and Control for Aerospace Equipment, T.O. 1-1-2 (Robins AFB, GA: Warner Robins ALC/MMEDT, 1984), pp. 5-8.

[4]Ibid., pp. 5-8.

[5]Childers, et al.

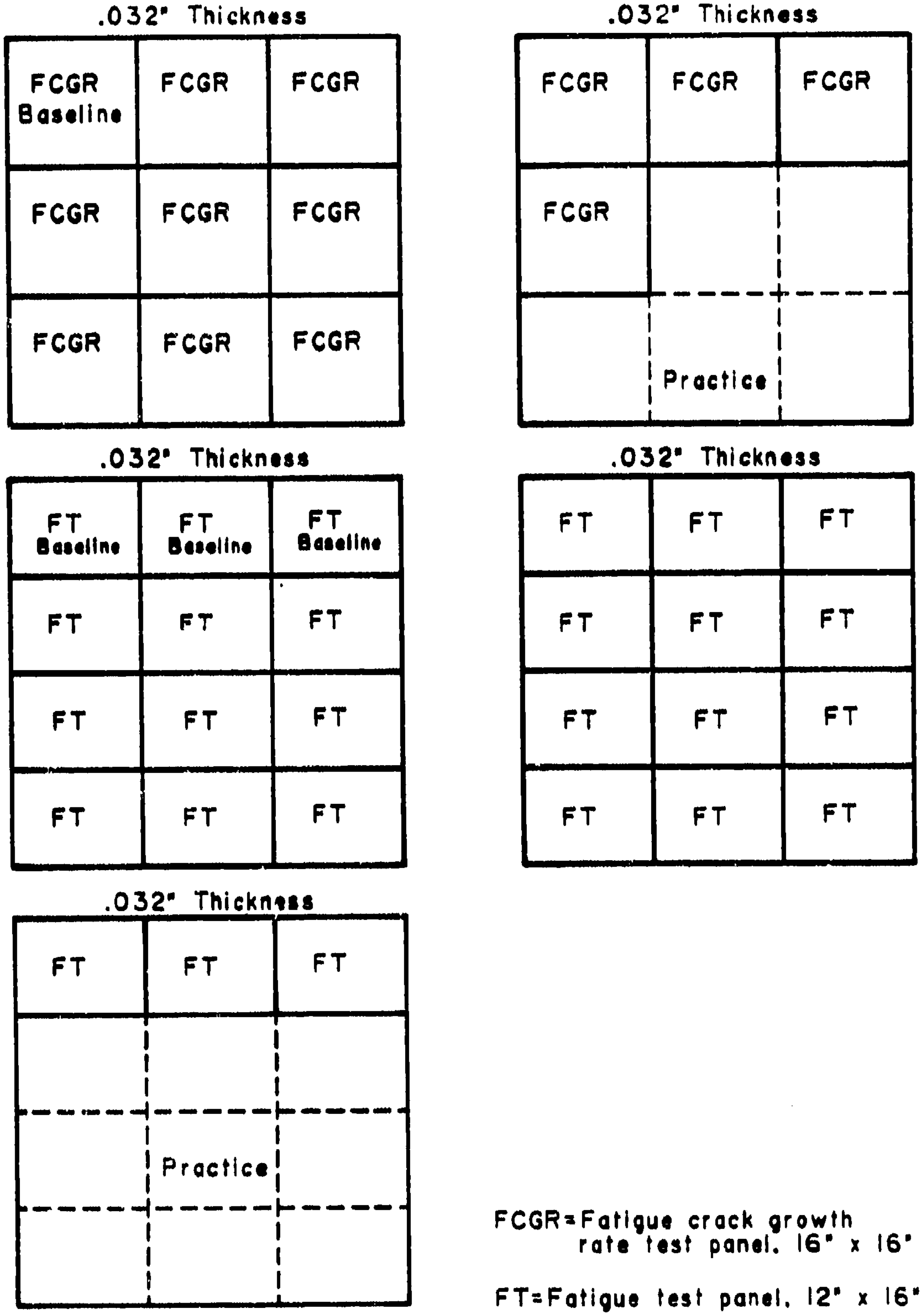
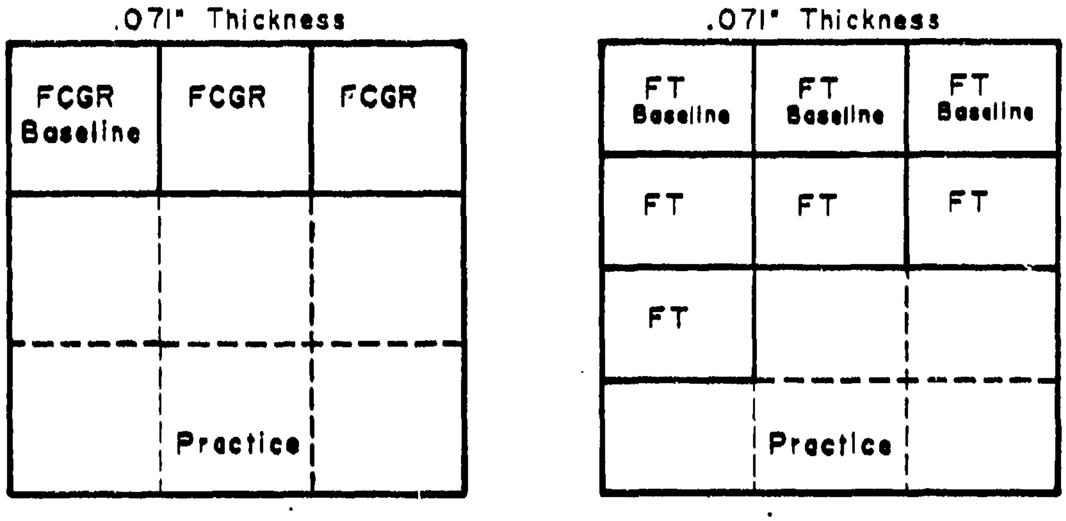


Figure 2a.

DIVISION OF 48" X 48" ALUMINUM SHEETS INTO TEST PANELS

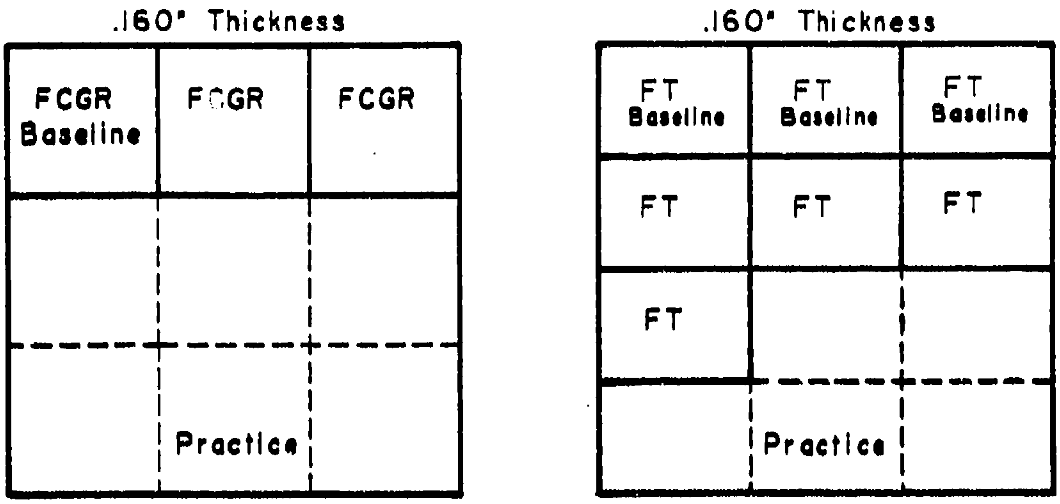


FCGR=Fatigue crack growth rate test panel, 16" x 16"

FT=Fatigue test panel, 12" x 16"

Figure 2b.

DIVISION OF 48" X 48" ALUMINUM SHEETS INTO TEST PANELS, CONT'D



FCGR=Fatigue crack growth rate test panel, 16" x 16"

FT=Fatigue test panel, 12" x 16"

Figure 2c.

DIVISION OF 48" X 48" ALUMINUM SHEETS INTO TEST PANELS, CONT'D

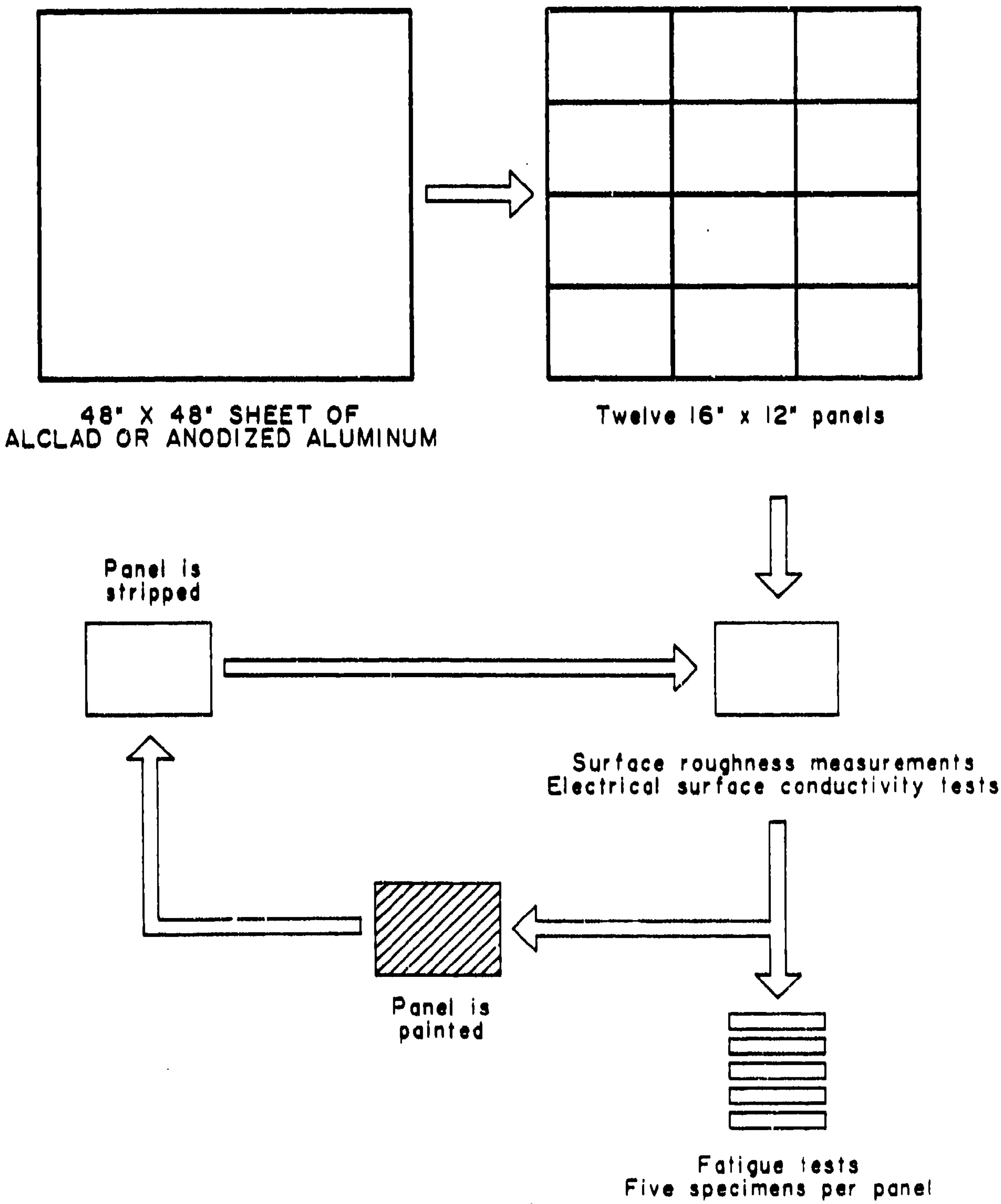


Figure 3.

FLOWCHART FOR FATIGUE TEST SPECIMENS

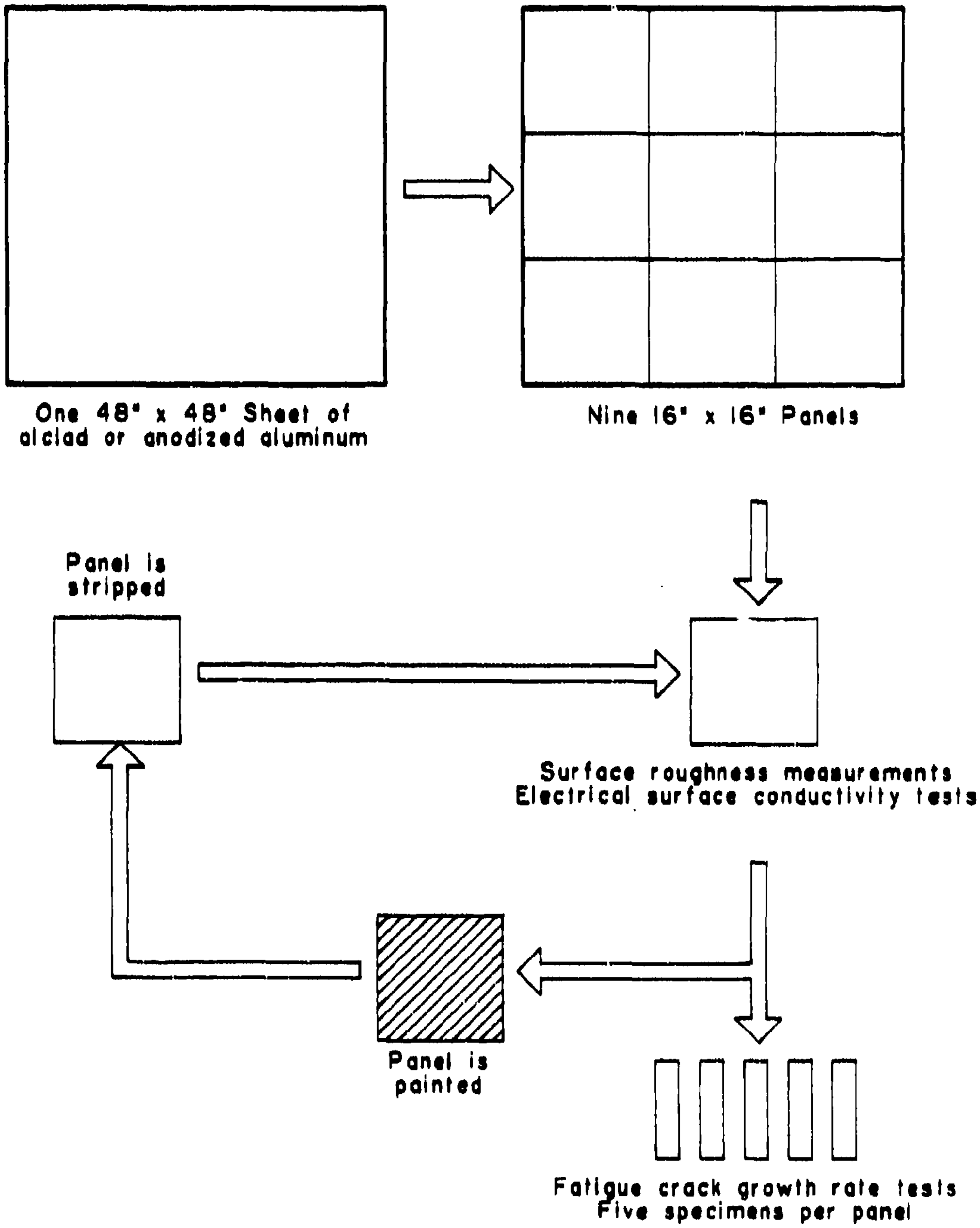


Figure 4.

FLOWCHART FOR FATIGUE CRACK GROWTH RATE SPECIMENS

14.1078.029

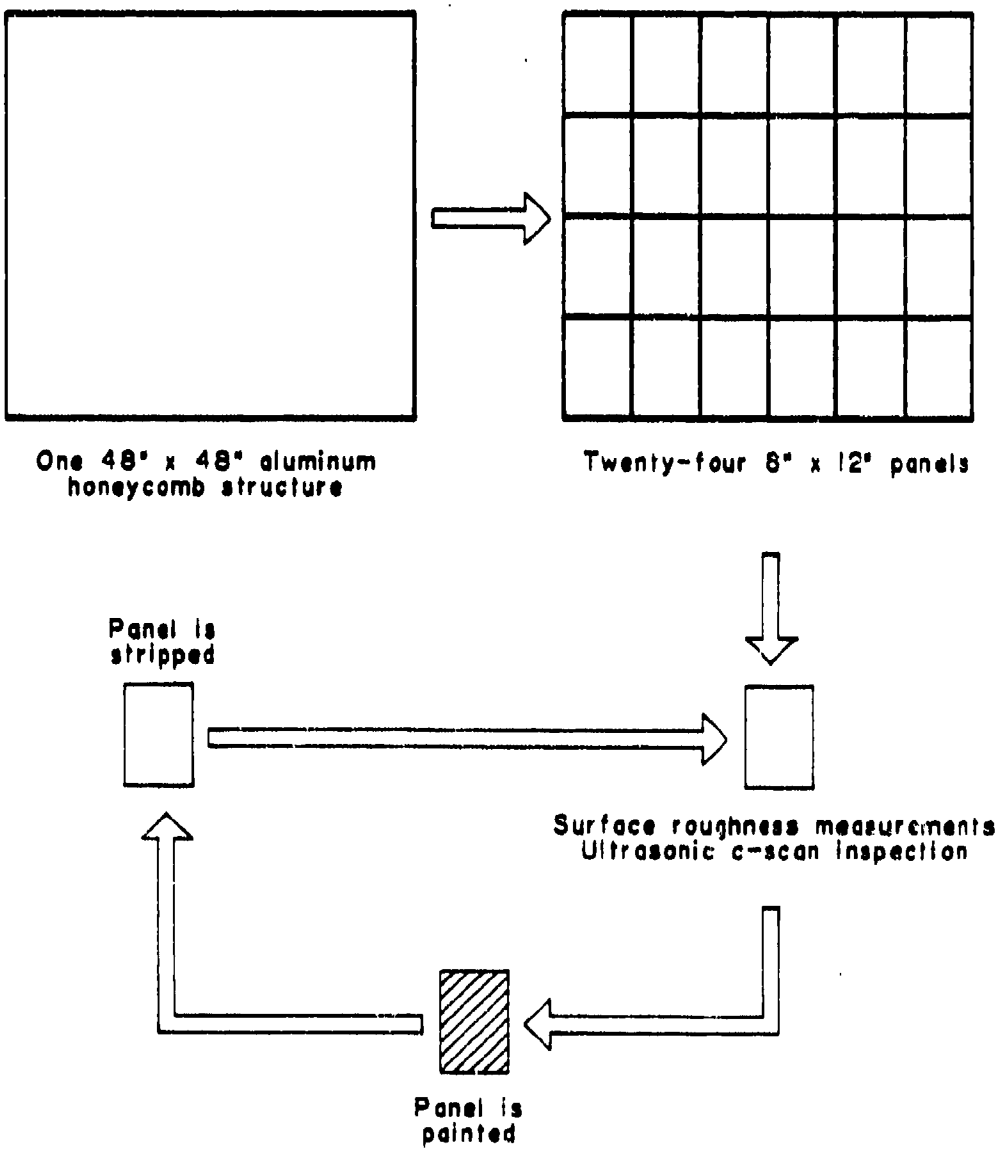


Figure 5.
FLOWCHART FOR ALUMINUM HONEYCOMB

14.1078.028

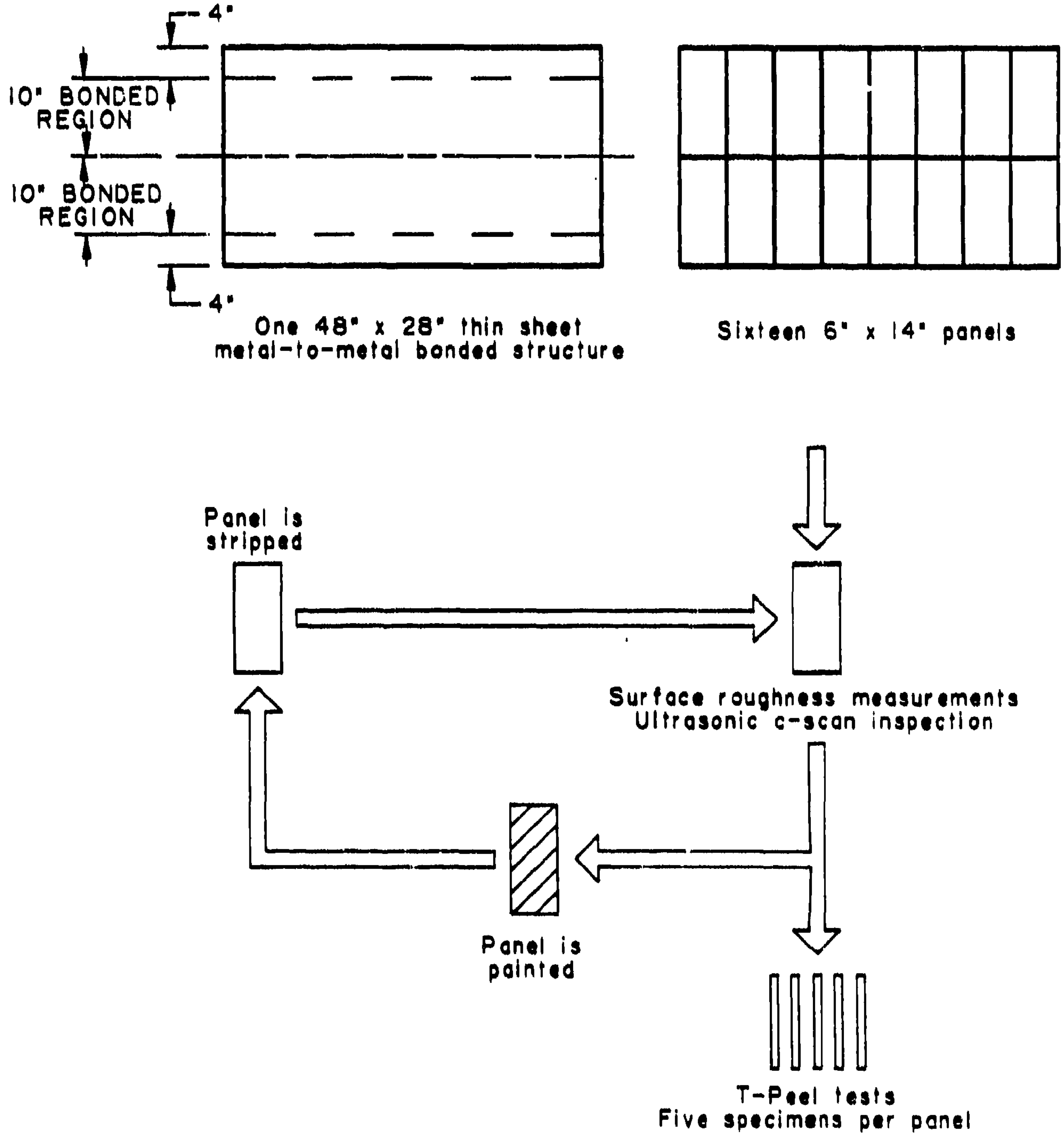
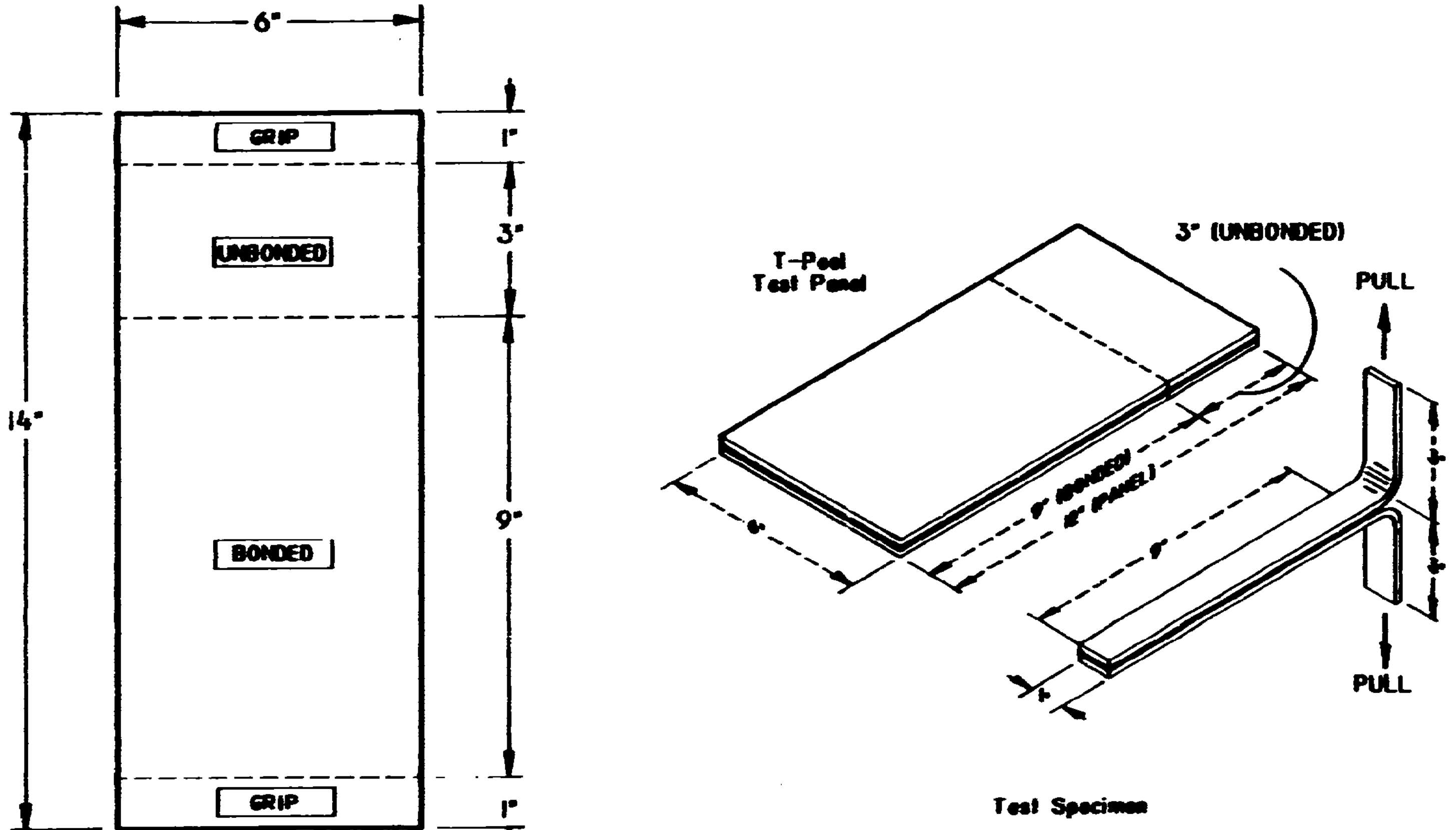


Figure 6.

FLOWCHART FOR THIN SHEET METAL-TO-METAL BONDED STRUCTURE



Test Panel

Test Specimen

Grip sections to be removed and panel to be divided into five 12" x 1" T-Peel specimens

Figure 7.
THIN SHEET METAL-TO-METAL BONDED ALUMINUM STRUCTURE

14J078.015

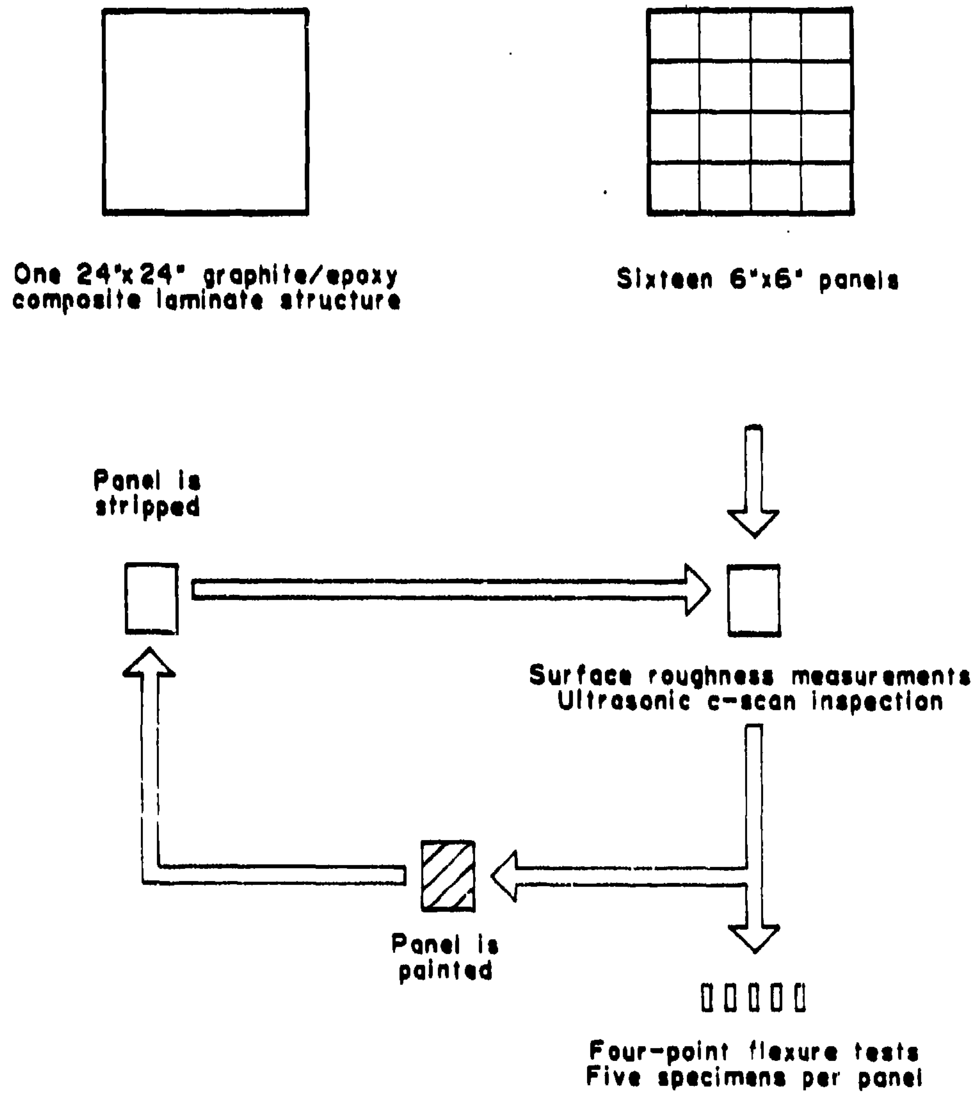


Figure 8.
FLOWCHART FOR GRAPHITE/EPOXY COMPOSITE SPECIMENS

14.1078.031

TABLE 1. EXISTING DATA ON PAINT STRIPPING PROCESSES

Criterion	Plastic Media	Laser	Dry Ice
Efficiency of Coating Removal	***	***	**
Degree of Surface Roughness Generated on Metallic and non-metallic materials	***	*	*
Extent of Damage to Clad, Anodized, and Alodined Aluminum Surfaces	***	***	*
Extent of Damage to Advanced Composite and other Non-Metallic Surfaces	***	***	*
Adaptability to Automation	**	**	*
Capital Equipment Costs Including Air Logistic Center (ALC) Site Preparation and Implementation Costs	***	**	**
Generating Costs (both Direct and Indirect)	***	**	**
Flexibility of the System for Batch Processing	**	*	*
Environmental and Personnel Safety	***	**	*
Level of Operator and Maintenance Personnel Expertise Required	***	**	**
Projected Cost Savings Vis-a-Vis Conventional Chemical Stripping	***	**	*

*** - Statistically confirmed data exists
** - Quantitative data exists
* - Qualitative data exists

TABLE 2. PROCESS SELECTION CRITERIA

Criterion	Plastic Media	Laser	Dry Ice
Efficiency of Coating Removal	C (Battelle)	D	D
Degree of Surface Roughness Generated on Metallic and non-metallic materials	C (Battelle & G.D.)	D	D
Extent of Damage to Clad, Anodized, and Alodined Aluminum Surfaces	C (G.D.)	D	D
Extent of Damage to Advanced Composite and other Non-Metallic Surfaces	C (G.D.)	D	D
Adaptability to Automation	M	I,M	I,M
Capital Equipment Costs Including Air Logistic Center (ALC) Site Preparation and Implementation Costs	A,M	I,A,M	I,A,M
Generating Costs (both Direct and Indirect)	A	I,A	I,A
Flexibility of the System for Batch Processing	M	I,M	I,M
Environmental and Personnel Safety	C (Port Huaneme)	I,A	I,A
Level of Operator and Maintenance Personnel Expertise Required	A	I	I
Projected Cost Savings Vis-a-Vis Conventional Chemical Stripping	A	A	A

D - Directly addressed by test plan
I - Indirectly addressed by test plan
A - Addressed by A.C.C. economic analysis
M - Addressed by in-house modeling
C - Currently being addressed by other concurrent contract

TABLE 3. QUANTITY OF MATERIALS TO BE PROCURED/FABRICATED

MATERIAL	THICKNESS	DIMENSIONS	QUANTITY
7075-T6 Alclad	.032"	48" x 48"	5
	.071"	"	2
	.160"	"	2
7075-T6 Anodized	.032"	"	5
	.071"	"	2
	.160"	"	2
2024-T3 Alclad	.032"	"	5
	.071"	"	2
	.160"	"	2
2024-T3 Anodized	.032"	"	5
	.071"	"	2
	.160"	"	2
Aluminum Honeycomb	.532"	"	1
Thin Sheet Bonded Structure	.032"	28" x 48"	2
Graphite/Epoxy Composite	8-Ply	24" x 24"	2
	12-Ply	"	1
	80-Ply	"	1

SUMMARY OF MATERIALS TO BE PROCURED/FABRICATED

Aluminum Sheet	48" x 48"	16
Aluminum Honeycomb	"	1
Thin Sheet Bonded Structure	28" x 48"	2
Graphite/Epoxy Composite	24" x 24"	4

TABLE 4. QUANTITY OF PANELS TO BE FABRICATED

Material	Thickness (in.)	Undivided Sheets: Dimensions (in.)	Undivided Sheets: Quantity	Subdivided Panels: Dimensions (in.)	Subdivided Panels: Panels per Sheet	Subdivided Panels: Quantity
7075-T6 Alclad	.032"	48" x 48"	3	16" x 12"	12	36
		48" x 48"	2	16" x 16"	9	18
	.071"	48" x 48"	1	16" x 12"	12	12
		48" x 48"	1	16" x 16"	9	9
	.160"	48" x 48"	1	16" x 12"	12	12
		48" x 48"	1	16" x 16"	9	9
7075-T6 Anodized	.032"	48" x 48"	3	16" x 12"	12	36
		48" x 48"	2	16" x 16"	9	18
	.071"	48" x 48"	1	16" x 12"	12	12
		48" x 48"	1	16" x 16"	9	9
	.160"	48" x 48"	1	16" x 12"	12	12
		48" x 48"	1	16" x 16"	9	9
2024-T3	.032"	48" x 48"	3	16" x 12"	12	36
		48" x 48"	2	16" x 16"	9	18
	.071"	48" x 48"	1	16" x 12"	12	12
		48" x 48"	1	16" x [illegible]	9	9
	.160"	48" x 48"	1	16" [illegible]	12	12
		48" x 48"	1	16" x 16"	9	9
2024-T3 Anodized	.032"	48" x 48"	3	16" x 12"	12	36
		48" x 48"	2	16" x 16"	9	18
	.071"	48" x 48"	1	16" x 12"	12	12
		48" x 48"	1	16" x 16"	9	9
	.160"	48" x 48"	1	16" x 12"	12	12
		48" x 48"	1	16" x 16"	9	9
Aluminum Honeycomb	.532"	48" x 48"	1	8" x 12"	24	24
Thin Sheet Bonded Structure	.032"	28" x 48"	2	6" x 14"	16	32
Graphite/Epoxy Composite	8-ply	24" x 24"	2	6" x 6"	16	32
	12-ply	24" x 24"	1	6" x 6"	16	16
	80-ply	24" x 24"	1	6" x 6"	16	16

SUMMARY OF PANELS TO BE FABRICATED

Aluminum Sheet	48" x 48"	20	16" x 12"	240
	48" x 48"	16	16" x 16"	144
Aluminum Honeycomb	48" x 48"	1	8" x 12"	24
Thin Sheet Bonded Structure	28" x 48"	2	6" x 14"	32
Graphite/Epoxy Composite	24" x 24"	4	6" x 6"	64

TABLE 5. QUANTITY OF SPECIMENS TO BE MECHANICALLY TESTED

		FATIGUE TEST SPECIMENS (1)					CRACK GROWTH RATE SPECIMENS					T-PEEL BOND STRENGTH TEST SPECIMENS					FOUR-POINT FLEXURE TEST SPECIMENS				
Material	Thickness inch	Base-line	CYCLE 1	2	3	4	Base-line	CYCLE 1	2	3	4	Base-line	CYCLE 1	2	3	4	Base-line	CYCLE 1	2	3	4
7075-T6 Alclad	.032	15	30	30	30	30	5	15	15	15	15										
	.071	15				20	5				10										
	.160	15				20	5				10										
7075-T6 Anodized	.032	15	30	30	30	30	5	15	15	15	15										
	.071	15				20	5				10										
	.160	15				20	5				10										
2024-T3 Alclad	.032	15	30	30	30	30	5	15	15	15	15										
	.071	15				20	5				10										
	.160	15				20	5				10										
2024-T3 Anodized	.032	15	30	30	30	30	5	15	15	15	15										
	.071	15				20	5				10										
	.160	15				20	5				10										
7075-T6 Aluminum Alclad Honeycomb	.532																				
Thin Sheet Metal-to-Metal Bond. Structure	.032											5	15	15	15	15					
Graphite/ Epoxy Composite	8-Ply																5	15	15	15	15
	12-Ply																5	10	10	10	1[illegible]
	80-Ply																5	10	10	10	1[illegible]

(1) Half of these tests are at high stress and half are at low stress.

TABLE 6. QUANTITY OF PANELS SURFACE TESTED IN EACH CYCLE

Material	Thickness (in.)	Dimensions (in.)	Surface Conductivity as Rec'd	Surface Conductivity CYCLE 1	2	3	4	Surface Roughness as Rec'd	Surface Roughness CYCLE 1	2	3	4
7075-T6 Alclad	.032	16 x 12						6	6	6	6	6
	.032	16 x 16						3	3	3	3	3
	.071	16 x 12						4	4	4	4	4
	.071	16 x 16						2	2	2	2	2
	.160	16 x 12						4	4	4	4	4
	.160	16 x 16						2	2	2	2	2
7075-T6 Anodized	.032	16 x 12	6	6	6	6	6	6	6	6	6	6
	.032	16 x 16	3	3	3	3	3	3	3	3	3	3
	.071	16 x 12	4	4	4	4	4	4	4	4	4	4
	.071	16 x 16	2	2	2	2	2	2	2	2	2	2
	.160	16 x 12	4	4	4	4	4	4	4	4	4	4
	.160	16 x 16	2	2	2	2	2	2	2	2	2	2
2024-T3 Alclad	.032	16 x 12						6	6	6	6	6
	.032	16 x 16						3	3	3	3	3
	.071	16 x 12						4	4	4	4	4
	.071	16 x 16						2	2	2	2	2
	.160	16 x 12						4	4	4	4	4
	.160	16 x 16						2	2	2	2	2
2024-T3 Anodized	.032	16 x 12	6	6	6	6	6	6	6	6	6	6
	.032	16 x 16	3	3	3	3	3	3	3	3	3	3
	.071	16 x 12	4	4	4	4	4	4	4	4	4	4
	.071	16 x 16	2	2	2	2	2	2	2	2	2	2
	.160	16 x 12	4	4	4	4	4	4	4	4	4	4
	.160	16 x 16	2	2	2	2	2	2	2	2	2	2
Aluminum Honeycomb		8 x 12						6	6	6	6	6
Thin Sheet Bonded		6 x 14						3	3	3	3	3
Graphite Composite	8-Ply	6 x 6						3	3	3	3	3
	12-Ply	6 x 6						2	2	2	2	2
	80-Ply	6 x 6						2	2	2	2	2

SUMMARY OF PANELS SURFACE TESTED IN EACH CYCLE

Material	Dimensions (in.)	Surface Conductivity as Rec'd	Surface Conductivity CYCLE 1	2	3	4	Surface Roughness as Rec'd	Surface Roughness CYCLE 1	2	3	4
Aluminum Sheet	16 x 12	28	28	28	28	28	56	56	56	56	56
	16 x 16	14	14	14	14	14	28	28	28	28	28
Aluminum Honeycomb	8 x 12						6	6	6	6	6
Thin Sheet Bonded	6 x 14						3	3	3	3	3
Graphite Composite	6 x 6						7	7	7	7	7

TABLE 7. QUANTITY OF PANELS PAINTED IN EACH CYCLE

Material	Thickness (in.)	Dimensions (in.)	Practice Panels	PAINT/STRIP CYCLE 1	2	3	4
7075-T6 Alclad	.032	16 x 12	9	24	18	12	6
	.032	16 x 16	5	12	9	6	3
	.071	16 x 12	5	4	4	4	4
	.071	16 x 16	6	2	2	2	2
	.160	16 x 12	5	4	4	4	4
	.160	16 x 16	6	2	2	2	2
7075-T6 Anodized	.032	16 x 12	9	24	18	12	6
	.032	16 x 16	5	12	9	6	3
	.071	16 x 12	5	4	4	4	4
	.071	16 x 16	6	2	2	2	2
	.160	16 x 12	5	4	4	4	4
	.160	16 x 16	6	2	2	2	2
2024-T3 Alclad	.032	16 x 12	9	24	18	12	6
	.032	16 x 16	5	12	9	6	3
	.071	16 x 12	5	4	4	4	4
	.071	16 x 16	6	2	2	2	2
	.160	16 x 12	5	4	4	4	4
	.160	16 x 16	6	2	2	2	2
2024-T3 Anodized	.032	16 x 12	9	24	18	12	6
	.032	16 x 16	5	12	9	6	3
	.071	16 x 12	5	4	4	4	4
	.071	16 x 16	6	2	2	2	2
	.160	16 x 12	5	4	4	4	4
	.160	16 x 16	6	2	2	2	2
Aluminum Honeycomb	.532	8 x 12	18	6	6	6	6
Thin Sheet Bonded	.032	6 x 14	19	12	9	6	3
Graphite Composite	8-Ply	6 x 6	19	12	9	6	3
	12-Ply	6 x 6	7	8	6	4	2
	80-Ply	6 x 6	7	8	6	4	2

SUMMARY OF PAINTED PANELS

	Dimensions	Practice Panels	1	2	3	4
Aluminum Sheet	16 x 12	76	128	104	80	56
	16 x 16	68	64	52	40	28
Aluminum Honeycomb	8 x 12	18	6	6	6	6
Thin Sheet Bonded	6 x 14	19	12	9	6	3
Graphite Composite	6 x 6	33	28	21	14	7
TOTAL		214	238	192	146	100

TABLE 8a. QUANTITY OF PANELS LASER STRIPPED IN EACH CYCLE

Material	Thickness (in.)	Dimensions (in.)	PAINT/STRIP CYCLES 1 Optimal	1 Over-exp.	2 Optimal	2 Over-exp.	3 Optimal	3 Over-exp.	4 Optimal	4 Over-exp.
7075-T6	.032	16 x 12	8	8	6	6	4	4	2	2
Alclad	.032	16 x 16	4	4	3	3	2	2	1	1
	.071	16 x 12	2		2		2		2	
	.071	16 x 16	1		1		1		1	
	.160	16 x 12	2		2		2		2	
	.160	16 x 16	1		1		1		1	
7075-T6	.032	16 x 12	8	8	6	6	4	4	2	2
Anodized	.032	16 x 16	4	4	3	3	2	2	1	1
	.071	16 x 12	2		2		2		2	
	.071	16 x 16	1		1		1		1	
	.160	16 x 12	2		2		2		2	
	.160	16 x 16	1		1		1		1	
2024-T3	.032	16 x 12	8	8	6	6	4	4	2	2
Alclad	.032	16 x 16	4	4	3	3	2	2	1	1
	.071	16 x 12	2		2		2		2	
	.071	16 x 16	1		1		1		1	
	.160	16 x 12	2		2		2		2	
	.160	16 x 16	1		1		1		1	
2024-T3	.032	16 x 12	8	8	6	6	4	4	2	2
Anodized	.032	16 x 16	4	4	3	3	2	2	1	1
	.071	16 x 12	2		2		2		2	
	.071	16 x 16	1		1		1		1	
	.160	16 x 12	2		2		2		2	
	.160	16 x 16	1		1		1		1	
Alum. Honeycomb		8 x 12	2	2	2	2	2	2	2	2
Thin Sheet Bonded		6 x 14	4	4	3	3	2	2	1	1
Graphite	8-Ply	6 x 6	4	4	3	3	2	2	1	1
Composite	12-Ply	6 x 6	4		3		2		1	
	80-Ply	6 x 6	4		3		2		1	

SUMMARY OF LASER STRIPPED PANELS

		1 Optimal	1 Over-exp.	2 Optimal	2 Over-exp.	3 Optimal	3 Over-exp.	4 Optimal	4 Over-exp.
Aluminum Sheet	16 x 12	48	32	40	24	32	16	24	8
	16 x 16	24	16	20	12	16	8	12	4
Honeycomb	8 x 12	2	2	2	2	2	2	2	2
Thin Sheet Bond	6 x 14	4	4	3	3	2	2	1	1
Graphite Composite	6 x 6	12	4	9	3	6	2	3	1
TOTAL		90	22	74	20	58	18	42	16

TABLE 8b. QUANTITY OF PANELS DRY ICE STRIPPED IN EACH CYCLE

Material	Thickness (in.)	Dimensions (in.)	PAINT/STRIP CYCLE 1	2	3	4
7075-T6 Alclad	.032	16 x 12	8	6	4	2
	.032	16 x 16	4	3	2	1
	.071	16 x 12	2	2	2	2
	.071	16 x 16	1	1	1	1
	.160	16 x 12	2	2	2	2
	.160	16 x 16	1	1	1	1
7075-T6 Anodized	.032	16 x 12	8	6	4	2
	.032	16 x 16	4	3	2	1
	.071	16 x 12	2	2	2	2
	.071	16 x 16	1	1	1	1
	.160	16 x 12	2	2	2	2
	.160	16 x 16	1	1	1	1
2024-T3 Alclad	.032	16 x 12	8	6	4	2
	.032	16 x 16	4	3	2	1
	.071	16 x 12	2	2	2	2
	.071	16 x 16	1	1	1	1
	.160	16 x 12	2	2	2	2
	.160	16 x 16	1	1	1	1
2024-T3 Anodized	.032	16 x 12	8	6	4	2
	.032	16 x 16	4	3	2	1
	.071	16 x 12	2	2	2	2
	.071	16 x 16	1	1	1	1
	.160	16 x 12	2	2	2	2
	.160	16 x 16	1	1	1	1
Aluminum Honeycomb	.532	8 x 12	2	2	2	2
Thin Sheet Bonded	.032	6 x 14	4	3	2	1
Graphite Composite	8-Ply	6 x 6	4	3	2	1
	12-Ply	6 x 6	4	3	2	1
	80-Ply	6 x 6	4	3	2	1

SUMMARY OF DRY ICE STRIPPED PANELS

Aluminum Sheet	16 x 12	48	40	32	24
	16 x 16	24	20	16	12
Aluminum Honeycomb	8 x 12	2	2	2	2
Thin Sheet Bonded	6 x 14	4	3	2	1
Graphite Composite	6 x 6	12	9	6	3
TOTAL		90	74	58	42

TABLE 9. PROCESS SELECTION TEST PLAN

Mechanical Testing Standards

MATERIAL	TEST	STANDARD	PANEL DIMS	SPECIMEN DIMS
1. Aluminum Sheet Aluminum Honeycomb Thin Sheet Bonded Structure Graphite Composite	Surface Roughness Measurements	Test Plan	16 x 12 8 x 12 6 x 14 6 x 6	16 x 12 8 x 12 6 x 14 6 x 6
2. Aluminum Anodized .032 .071 .160	Surface Electrical Conductivity Tests	Test Plan	16 x 12	16 x 12
3. Aluminum Honeycomb Thin Sheet Bonded Structure Graphite/Epoxy Composite	Ultrasonic C-scan Inspections	Test Plan	6 x 6	6 x 6
4. Aluminum Alclad & Anodized .032 .071 .160	Fatigue Tests	ASTM E 466-82	16 x 12	2 X 12½
5. Aluminum Alclad & Anodized .032 .071 .160	Fatigue Crack Growth Rate Tests	ASTM E 647-83	16 x 16	3x12-1/2
6. Metal-to-Metal Thin Sheet Bonded Aluminum Structure	T-Peel Bond Strength Tests	ASTM D1876-72	6 x 14	12 x 1
7. Graphite/Epoxy Composite	Four-Point Flexure Tests	ASTM D790-84a, Method II	6 x 6	3 x 1

APPENDIX B

PROCESS OPTIMIZATION TECHNICAL OPERATING REPORT

SOUTHWEST RESEARCH INSTITUTE
Post Officer Drawer 28510, 6220 Culebra Road
San Antonio, Texas 78284

ROBOTIC PAINT STRIPPER CELL (RPSC)

TECHNICAL OPERATING REPORT (TOR)
PROCESS OPTIMIZATION

SwRI Project No. 14-1078
Contract No. F33615-86-C-5044

Submitted by:
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August 7, 1987

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PROCESS OPTIMIZATION

SUMMARY AND RECOMMENDATIONS

This report includes summaries of previous DOD reports and experiences with Plastic Media Blast (PMB) paint stripping, the results of robotic PMB paint stripping tests performed at SwRI between December 1986 and March 1987, and recommendations for design and process parameters.

Various DOD repair facilities (Air Force, Army, and Navy) have accumulated several years experience with manual PMB paint stripping. Nearly all stripping is performed using 30/40 sieve, 3.5 mohs media, although 3.0 mohs is used for composites. Nozzles used range form 1/4" to 1/2" with 1/2" being the most common. Nozzle pressures range from 20 psi to 45 psi with the lower pressures generally used for composite material. Nozzle angle and standoff distance are varied by the operators depending on the material and the condition of the paint with angles ranging from 90° to 45° from normal and standoff distances ranging from 12 to 48 inches.

PMB paint stripping tests were performed at SwRI using three different commercial systems. In all cases the blast nozzle was mounted on a Cincinnati-Milacron T3-566 robot so that standoff distance, angle and velocity could be accurately controlled. The velocity and the mass flow rate of the plastic beads were measured for different nozzle pressures and media control valve settings. Stripping test were performed using a variety of aircraft material while varying nozzle pressures, media flow rate, nozzle angle, standoff distance, and robot velocity. Tests were directed toward determining the operating parameters that provided the fastest paint removal rate without material damage.

Increasing nozzle pressure and media mass flow rate provide the greatest increase in the rate of paint removal. Larger mesh and harder plastic media increase the stripping rate to some extent. Standoff distance and nozzle angle can be varied over wide ranges without causing much effect on the stripping rate.

Based on these tests, the design of the Robotic Paint Stripper system includes two robots, with each having three nozzles of 1/2" diameter mounted on an end effector. The system will include the capability of operating

over a range of nozzle pressures, angles, standoff distances and mass flow rates. Recommended (optimal) operating parameters are:

PARAMETER	RECOMMENDED VALUE	OPERATIONAL RANGE
Media Size	30/40 sieve	depends on separation system
Media Hardness	3.5 mohs	3.0 to 4.0 mohs
Standoff Distance	24 inches	12 to 36 inches
Nozzle Pressure		20 to 40 psi
Aluminum	30 psi	
Composite	20 psi	
Mass Flow Rate		300 to 800 lbs/hr/nozzle
Aluminum	560 lb/hr/nozzle	
Composite	500 lb/hr/nozzle	
Nozzle Angle	Normal to surface	±45° from normal

Robot velocity will be adaptively controlled to compensate for differences in paint thickness and adhesion and will range from 75 inches/minute to 200 inches/minute. Paint removal rates will vary between 0.75 sq. ft./min. and 3.0 sq. ft./min. (per nozzle) depending on the substrate material and the thickness and condition of the paint. The average paint removal rate for the system (two robots, six nozzles) will be 9 square feet per minute.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

PROCESS OPTIMIZATION REPORT

1.0 INTRODUCTION

The objective of the Process Optimization subtask of the Robotic Paint Stripper Cell (RPSC) program is to optimize those critical process and equipment design variables and parameters that affect control of the organic coating removal process selected for automation. The plastic media paint stripping process was chosen over alternate paint stripping processes for the RPSC by an Air Force evaluation team consisting of Materials Laboratory, HQ Air Force Logistics Command (AFLC), and OO-ALC personnel.

The plastic media paint stripping process (a.k.a. plastic bead blasting) consists of small pneumatically-propelled, irregularly-shaped plastic particles impinging upon a painted surface, resulting in the removal of paint from that surface. There are several process variables in the plastic media paint stripping process. Among them are stand-off distance, nozzle pressure, nozzle diameter, nozzle shape, nozzle angle, nozzle velocity, plastic media velocity, plastic media mass flow rate, plastic media hardness, and plastic media size. Of course the nature of the substrate and the coating play a significant part. Within the limitations of time and financial constraints, we have found what appears to be the optimal combination of these process variables in the removal of aircraft paint and primer from aluminum and graphite composite substrates.

It would be naive to believe that a process as complex as plastic media paint stripping could be optimized in a laboratory setting and remain optimal for all variables in all real world situations. Therefore, our goal was to explore the behavioral trends of various coatings and substrates as we vary each of the most important process variables. From these observations, we have obtained three (3) important types of information:

1) the settings of certain variables for which the aircraft coatings in our specific tests were removed at the maximum rate, and

2) the identification of those variables in a robotic system which most effectively and/or most conveniently control the paint removal rate and limit the potential substrate damage.

3) the identification of those equipment and process variables which are ineffective and/or inconvenient in controlling the paint removal process and in limiting potential substrate damage.

2.0 PREVIOUS DATA

There has been in the last ten years a great deal of experience in the use of plastic media for the removal of paint from aircraft. In order to avoid duplication of effort, and at the same time provide parametric data necessary to support design as quickly as possible, we have assimilated and evaluated the data generated by those military facilities with the most relevant experience. The breadth of previous data created generalized guidelines for the useful range of several equipment and process variables; in particular media size, media hardness, nozzle diameter, nozzle pressure, nozzle angle, and nozzle stand-off (see Summary of Previous Data, Table 2-1).

2.1 Hill AFB Experience

Personnel at Hill AFB first began experimental plastic media paint stripping in 1981 with cadmium-plated steel, alclad aluminum, and anodized alclad aluminum test panels. Blasting pressures ranged from 50 to 100 PSI, and rate of travel varied between 18 and 72 inches/min. The first complete F-4 was stripped in 1984 using 12/16 (sieve size) media, 3.5 mohs, at about 60 PSI. The "standard" conditions in use today for F-4 airframes and components is 70% 30/40 media, 30% 12/16, 3.5 mohs hardness, 60-90° angle, 18-30 inch stand-off at 40 PSI, and 540 lbs/hr, with minimum dwell time necessary to remove paint.

2.2 U.S. Army Experience

The Corpus Christi Army Depot first began experimental plastic media paint stripping in 1983. They did their first complete aircraft (an OH-58 helicopter) in 1984. They used 30/40 media with 4.0 mohs hardness at 28 PSI. They have continued since then to do OH-58's with 30/40 media and 4.0 mohs hardness. Pressure ranges from 20 PSI on composites to 35 PSI on thick aluminum, but most typically they will strip at about 30 PSI. The presence of thicker aluminum, non-pressurized cabins, and low speed flight has allowed them to use 4.0 mohs hardness, but they may have to convert to 3.5 mohs depending upon the outcome of the ongoing Battelle characterization report.

They tell their operators to maintain a 14"-24" stand-off, a 45°-60° orientation, and about a 1-2 inch/sec. travel rate. They leave much of it to the operator. Their mass flow rate is about 400-500 lbs/hr.

2.3 U.S. Marines Experience

In 1986, the underside of a U.S. Marines AV8B Harrier was stripped with plastic media at Cherry Point NARF. The substrate was a combination metallic and graphite/epoxy composite. The pot pressure was 35 PSI, stand-off was 6-12", orientation was 10-30°, and the media was a combination of U.S. Technology Type III (4.0 mohs), U.S. Technology Polyextra (3.0 mohs),

TABLE 2-1. SUMMARY OF PREVIOUS DATA

FACILITY	MEDIA SIZE	MEDIA HARDNESS	NOZZLE DIAMETER	NOZZLE PRESSURE	NOZZLE ANGLE	NOZZLE STAND-OFF
HILL AIR FORCE BASE	12/16 AND 30/40	3.5 MOHS	1/2″	40 PSI	60-90°	18-30″
CORPUS CHRISTI ARMY DEPOT:						
COMPOSITES	30/40	4.0 MOHS	1/2″	20 PSI	45-60°	14-24″
ALUMINUM	″	″	″	35 PSI	″	″
CHERRY POINT NARF	30/40	3.5 MOHS	3/8″	30 PSI	60-90°	12-36″
NORTH ISLAND NARF						
COMPOSITES	30/40	3.0 MOHS	1/2″	45 PSI	90°	24-36″
ALUMINUM	″	3.0 MOHS OR 3.5 MOHS	″	″	″	″
NCEL REPORT						
COMPOSITES	30/40	3.0 MOHS	1/2″	40 PSI	45°	6-36″
ALUMINUM	″	3.5 MOHS	″	″	″	″
A.F.T.O 1F-4C-3-1-6						
FIBERGLASS	30/40	3.5 MOHS	1/4″	25 PSI	---	24-48″
ALUMINUM	″	″	1/2″	30-40 PSI	---	24-48″

and Composition Materials (3.5 mohs). All media was 30/40 sieve size. They concluded that the key to not damaging composites is to use low pressure and small sieve size.

2.4 U.S. Navy Experience

In 1984 several graphite/epoxy composite panels and graphite/epoxy-aluminum honeycomb panels from F/A-18's were plastic media stripped at Alameda NARF and mechanically tested at North Island NARF. Two types of media were used: U.S. Technology Polyextra (3.0 mohs) and U.S. Technology Polyplus (3.5 mohs). All media was 20/30 sieve size. Blast pressure was 40 PSI. A 5/16" diameter nozzle with a 4-6" stand-off was used for the Polyextra media, and a 1/2" diameter nozzle with a 12" stand-off was used for the Polyplus media. In 1985 North Island NARF performed further experimental plastic media paint stripping on graphite composite and aluminum panels. As a result of these tests, 3.0 or 3.5 mohs hardness media from U.S. Technology in the 30/40 sieve size was found to be best for steel, titanium, and aluminum. The 3.0 mohs hardness media in 30/40 sieve size was found to be the best for composites. The best settings for the other parameters were found to be: nozzle pressure 45 PSI ±5 PSI; stand-off distance - minimum necessary to remove paint (usually 24-36"); dwell time-minimum to remove topcoat and primer; orientation - perpendicular (90°).

2.5 The NCEL Report

In December, 1986 the Naval Civil Engineering Laboratory in Port Hueneme, CA published a report on the effectiveness of plastic media paint stripping for aircraft based upon the experiences of several users. They found that the usual blast parameters for the aircraft substrates are as follows:[1]

- Nozzle pressure of 40 psig is recommended.

- Media type/grit size: Polyextra (30/40 size, 3.0 mohs hardness) for fiberglass; Polyplus (30/40 size, 3.5 mohs hardness) for most substrates; Type III or Polyplus (11/16 size) for aggressive or glassbead type of operation.

- Stand-off distance is usually 6-8", and up to 3 feet.

- Angle of substrate to nozzle is usually at a 45° angle.

- Nozzle size of 1/2" diameter is recommended, and no lining is necessary.

2.6 Air Force Technical Order 1F-4C-3-1-6

The Air Force Technical Order (T.O.) 1F-4C-3-1-6 contains the instructions and parameters for depot level plastic media blast paint removal for F-4's. The T.O. calls for 30-40 PSI blasting pressure with 1/2" nozzle (25 PSI and 1/4" nozzle on fiberglass), stand-off distance of 2-4 ft., and 30/40 Poly-plus (3.5 mohs) media[2].

2.7 Conclusions Drawn From Previous Data

It was concluded from evaluating previous data that our optimization tests would stay within the following range of prescribed parameters:

Media size:	20/30 and 30/40 sieve size
Media hardness:	3.5 mohs hardness only
Nozzle diameters:	1/4" and 1/2"
Nozzle pressure:	10 PSI - 40 PSI
Nozzle angle:	70° - 90°
Nozzle stand-off:	3" - 36"

On the basis of previous data and numerous conversations with Air Force officials, we concluded that only within these ranges would a plastic media blast process satisfy three important requirements necessary for aircraft paint removal:

1) that the process remove paint effectively

2) that the process cause a minimum of substrate damage

3) that the process be acceptable to AFWAL, AFLC, and Hill AFB personnel.

3.0 SWRI LABORATORY TESTS

3.1 Purpose

The purpose of the SwRI laboratory tests was to supplement the previous data generated by other users and researchers, to establish trends of certain equipment and process design variables, and to explore the limits of paint removal.

3.2 Overview

The SwRI process optimization laboratory tests were conducted from December 1986 to March 1987. The specific details of the purpose, equipment, procedures, results, and conclusions of each test are described in Appendix A "Process Optimization Lab Notes" and will not be repeated here. Figure 3-1, however, provides a graphical overview of the equipment and process design variables which were the subjects of experimentation for each week of that time period. When a design variable ceased to be a subject of experimentation (e.g. see Nozzle Angle in Figure 3-1, fourth week of Dec. 1986), it was because we had reached a conclusion on that variable on the basis of our experience and previous data, or because it was felt that further experimentation in that area would add no further contribution to the actual design of the Robotic Paint Stripper.

3.3 Equipment, Procedures, and Objectives

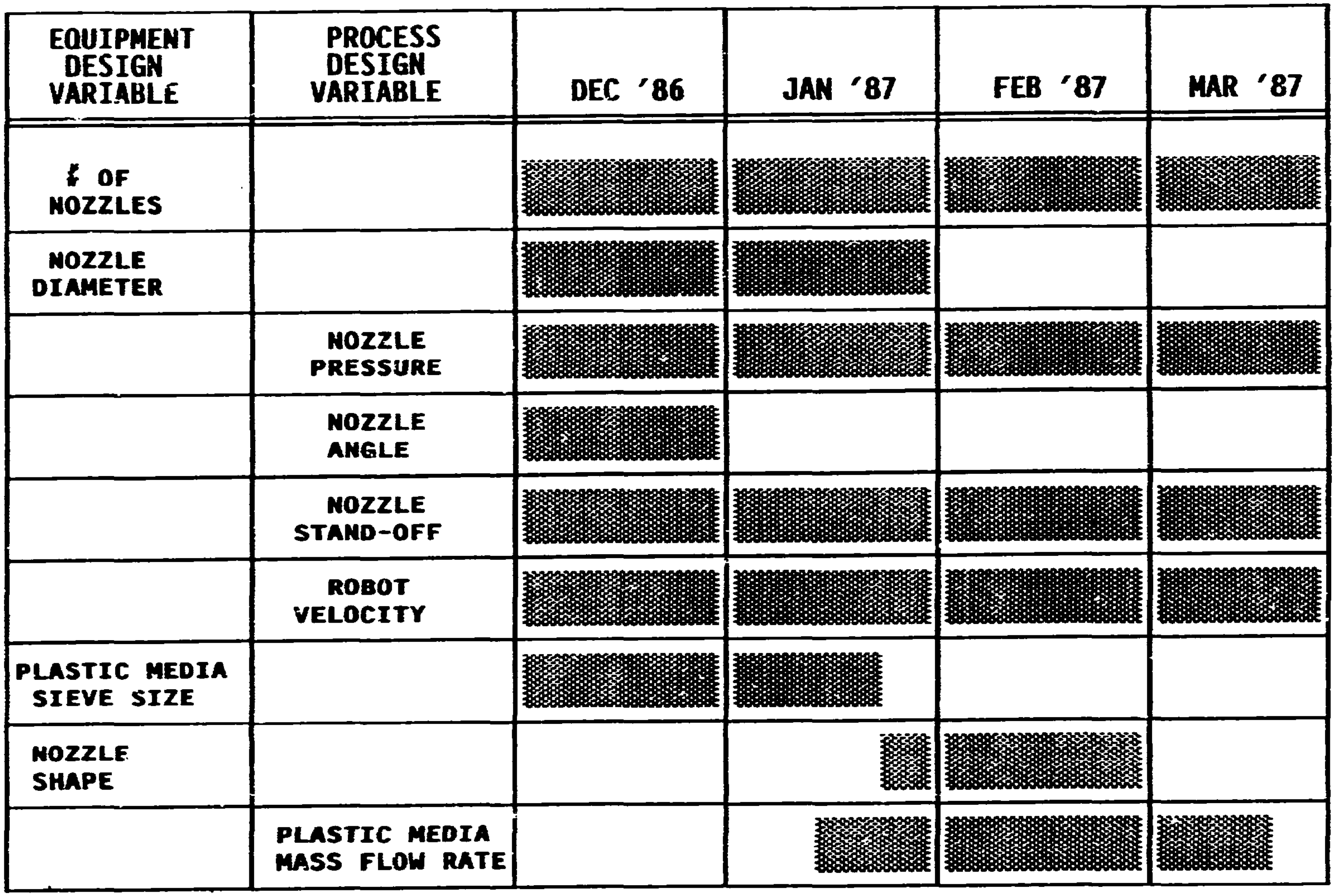
3.3.1 December 1986

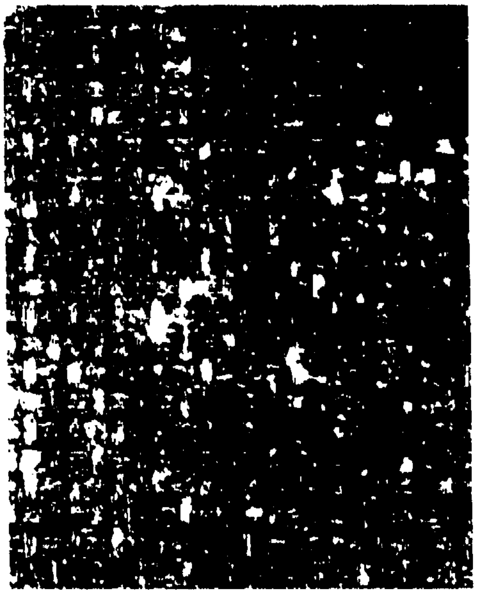
In December 1986, SwRI received a Blast'n Vac system from Turco, Inc. The concentric blast and vacuum nozzles were attached to the end of a Cincinnati-Milacron T3-566 hydraulic robot for experimental robotic paint stripping. The blast system included two Blast'n vac nozzle designs and was operated only in the closed-recovery mode, thus the stand-off distance was limited to the length of the shroud. The angle was also varied by cutting the bristles at the end of the vacuum shroud at the appropriate angle. The media was DuPont 30/40 sieve size, 3.5 mohs hardness.

The initial objective of the Blast 'n Vac system was to demonstrate the feasibility of robotic plastic media paint stripping. Plastic media had not yet been accepted by the Air Force as the chosen paint stripping method to be used by the Robotic Paint Stripper Cell. Tests were conducted at 20 PSI on graphite composite panels. Photomicrographs were taken up to 500x which showed no apparent fiber damage (see Figure 3-2) and an ultrasonic C-scan was performed which detected no subsurface damage (see Figure 3-3).

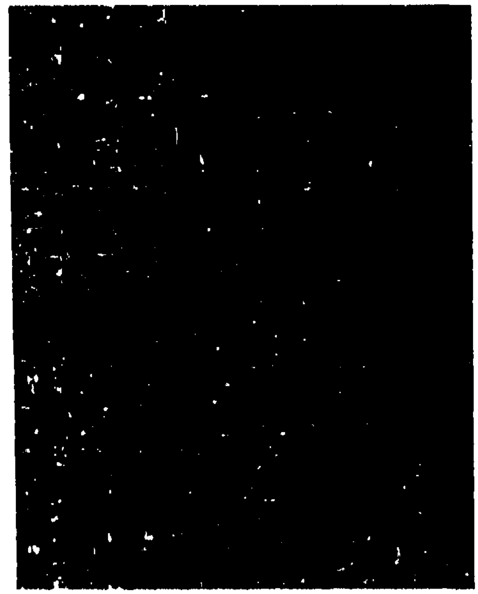
A secondary objective of the Blast 'N Vac tests was to establish paint removal trends. The painted panels were alclad aluminum and graphite composite. Because this system was used in closed recovery mode, nozzle angle, nozzle diameter, and nozzle stand-off were all equipment variables

FIGURE 3-1. OVERVIEW OF SWRI LABORATORY TESTS

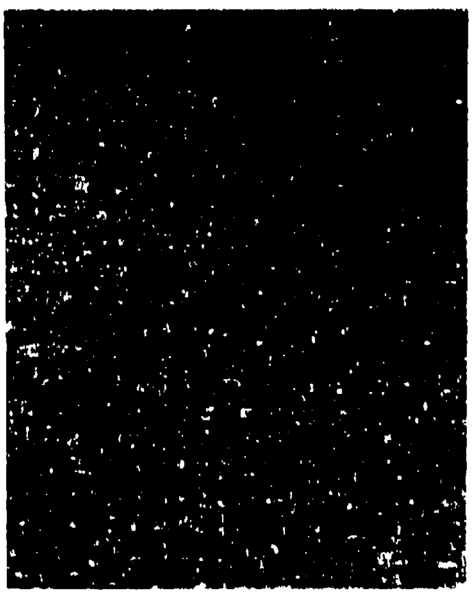




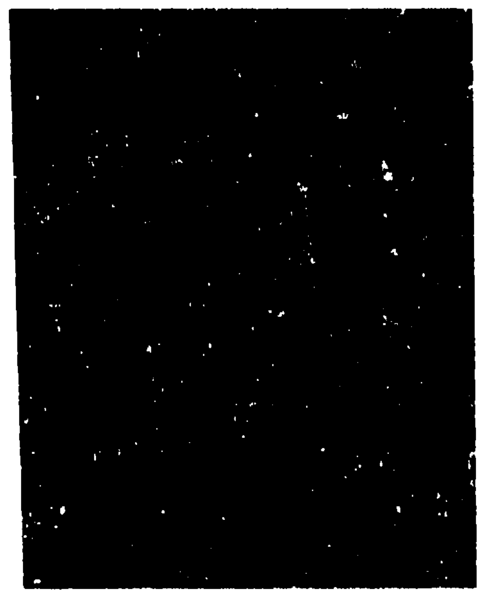
PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Travel Speed: 40 in/min. MAG: 10x



PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Travel Speed: 30 in/min. MAG: 10x



PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Travel Speed: 20 in/min. MAG: 10x



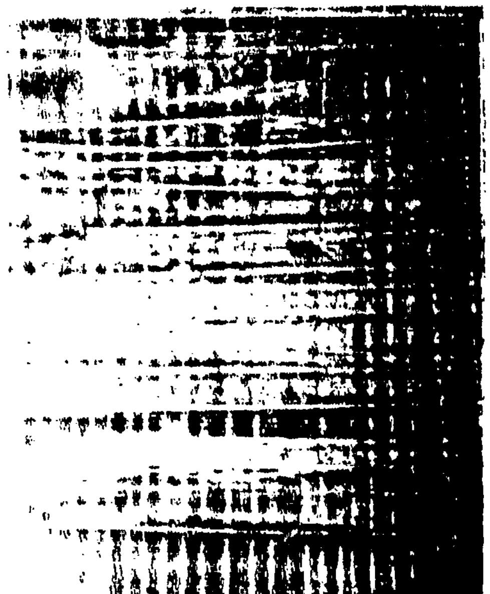
PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Travel Speed: 20 in/min. MAG: 50x

Figure 3-2a. Plastic Media Paint Stripping of Graphite Panel

PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Travel Speed: 20 in/min. MAG: 100X

PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Travel Speed: 20 in/min. MAG: 200X

PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Travel Speed: 20 in/min. MAG: 500x

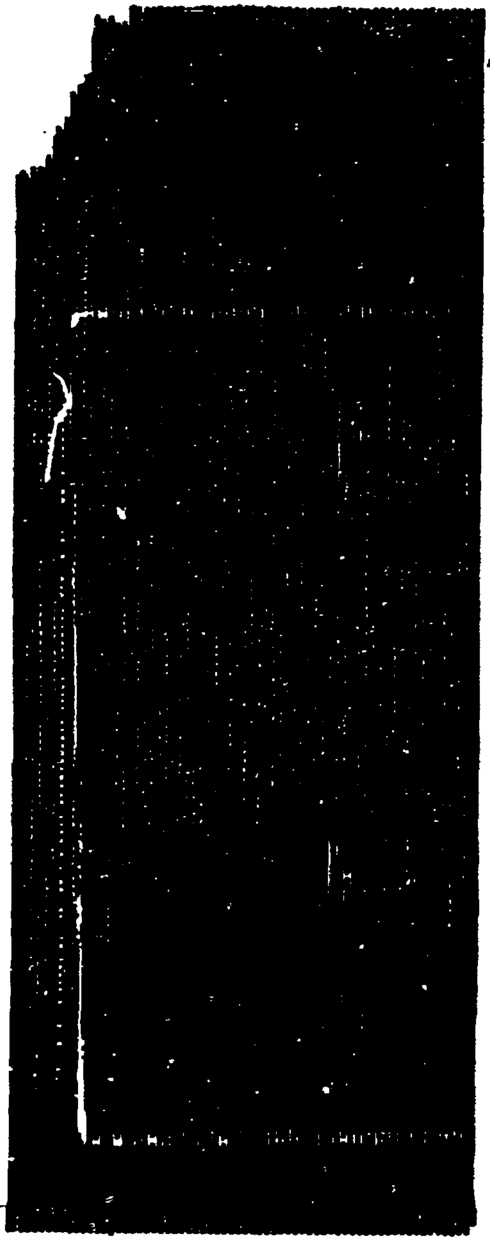


PLASTIC MEDIA BEAD-STRIPPING 12/12/86
Graphite Composite Panel, 8-ply
Baseline MAG: 500x

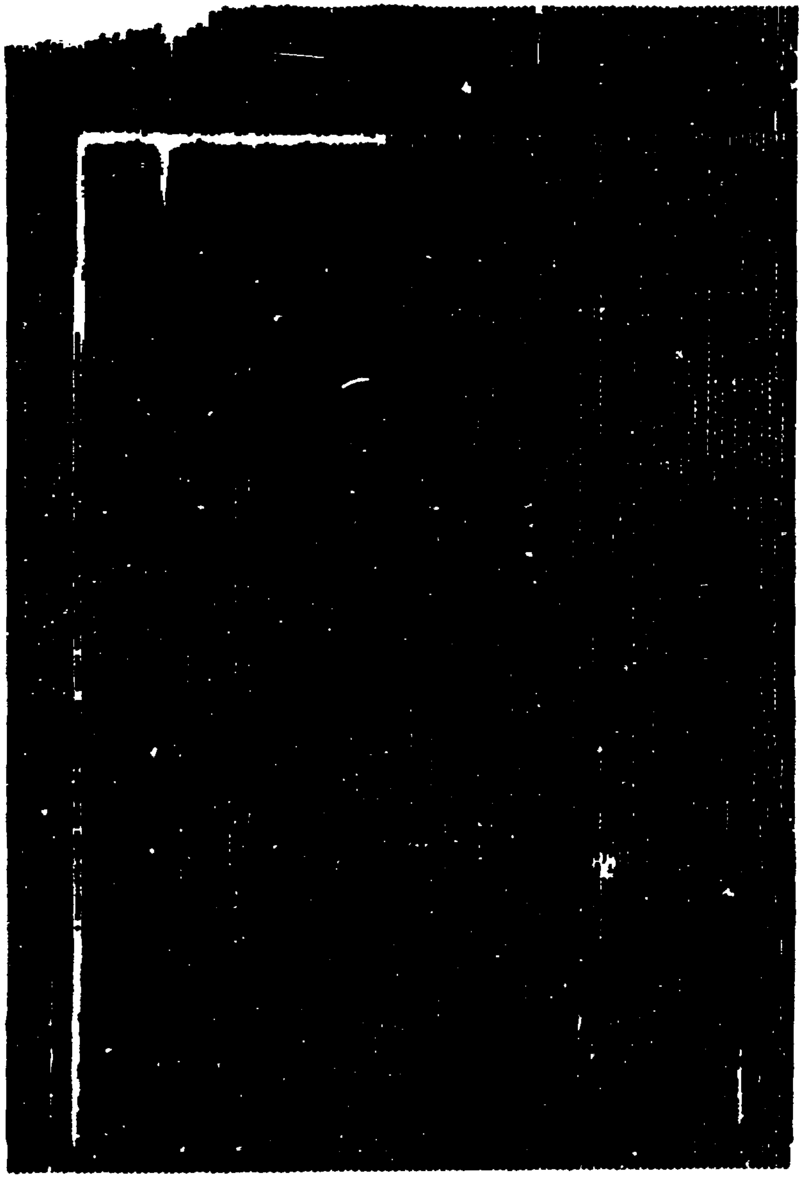
Figure 3-2b. Plastic Media Paint Stripping of Graphite Panel

Figure 3-3

GRAPHITE COMPOSITE ULTRASONIC C-SCANS



Impact damage from steel balls (for comparison only)



Graphite composite after plastic-media paint stripping

and remained constant during each paint test. Pot pressure and travel rate were the two process variables in these tests. Travel rate was readjusted after each test and pot pressure was changed after every four.

3.3.2 January-February 1987

The second blast system obtained was the Autostripper from Inventive Machine Corp. It was also attached to the Cincinnati Milacron robot, but unlike the Blast 'N Vac, was operated only in the open blast mode. The objectives of the tests conducted with the Autostripper were to:

1) measure bead velocity
2) measure mass flow rate
3) explore the effects of nozzle shape, nozzle angle, nozzle stand-off, robot velocity, and nozzle pressure on paint removal rate for various substrates.

3.3.3 March 1987

The third and final blast system used in Process Optimization tests was the PMB-BV system from Schmidt Manufacturing. It, too, was attached to the Cincinnati Milacron robot and run in the open blast mode only. The panels used for these tests were the F-4 turtlebacks from Hill AFB (see illustration in Figure 3-4). The objectives of the tests run with the PMB-BV system were:

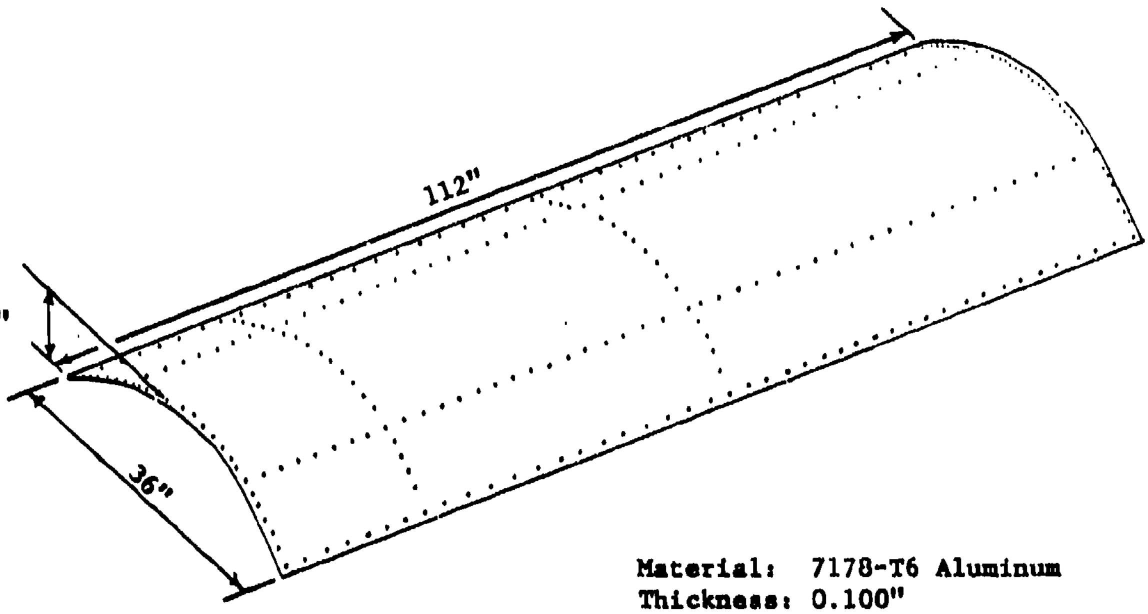
1) to calibrate the media control Thompson valve by measuring mass flow rates

2) to explore the effects of mass flow rate blast patterns, robot velocity, and nozzle stand-off on paint removal rate

3) to optimize swath spacing

4) to optimize mass flow rate, nozzle stand-off, robot velocity, and nozzle pressure for various substrates

5) to explore paint stripping of actual F-4 panels.



Material: 7178-T6 Aluminum
Thickness: 0.100"
Coatings: Zinc Chromate Primer and Acrylic Nitrocellulose Lacquer

Figure . Longest F-4 Turtleback

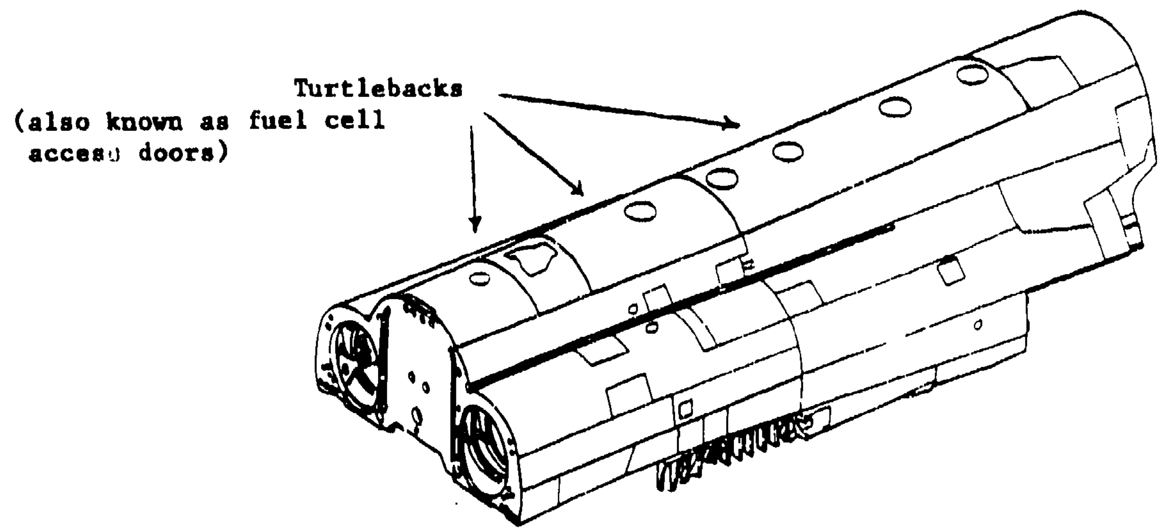


Figure 3-4. F-4 Center Fuselage

4.0 EQUIPMENT DESIGN VARIABLES

Early in the history of the RPSC project, it was decided to design this robot system around a two-robot concept with one robot stripping the right half of the aircraft (both top side and underside), and the second robot stripping the left half. It was also assumed that both robots would be designed identically, although in operation they would be independent. These assumptions (or conclusions) were made primarily because of the symmetry of military aircraft and the size limitations imposed by the paint stripping hangar at Hill AFB into which the RPSC must be installed. The two-robot concept had an important impact on the direction taken by the Process Optimization tests.

4.1 Number of Nozzles

Perhaps the most important of all equipment design variables which had to be addressed by Process Optimization was the appropriate number of nozzles to be included on each robot since this is a primary driver for end effector design. The number of nozzles required depends on four factors:

1) the average projected paint removal rate per nozzle

2) the desired overall RPSC paint removal rate

3) size constraints of the end effector and robot

4) the capacity of the bead blast facility to provide compressed air and recycled media.

It was calculated by a team composed of personnel from SwRI and Applied Concepts Corporation that to be economically competitive with manual bead blasting, the RPSC must remove on the average 5 ft^2/min from an F-4. It had long since been decided to use the two-robot concept; therefore, it was required that each robot should strip 2.5 ft^2/min. It seemed reasonable, furthermore, that the end effector, the robot, and the facilities could not support more than 5 nozzles per robot. A minimum paint removal rate of 0.5 ft^2/min was then established for a 5-nozzle end effector and 2.5 ft^2/min for a one-nozzle end effector. Table 4-1 shows the minimum paint removal rate (rounded to the nearest 1/2 ft^2/min) for the 1-, 2-, 3-, 4- and 5-nozzle designs.

TABLE 4-1. MINIMUM PAINT REMOVAL RATE PER ROBOT: 2.5 FT^2/MIN

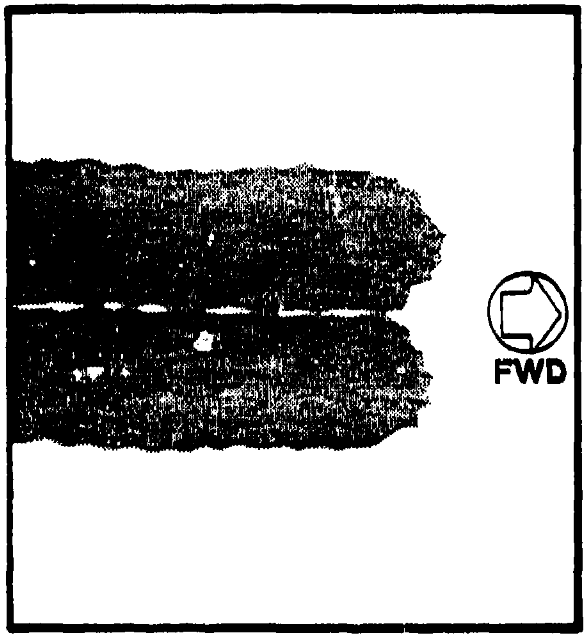
NUMBER OF NOZZLES PER ROBOT	PAINT REMOVAL REQUIRED PER NOZZLE
1	2.5 FT^2/MIN
2	1.5 FT^2/MIN
3	1.0 FT^2/MIN
4	0.75 FT^2/MIN
5	0.5 FT^2/MIN

It was discovered from the previous data of other facilities and from our early paint stripping experience that a minimum of 1.0 ft^2/min per nozzle was a very reasonable expectation and would not be difficult to achieve. Referring again to Table 4-1, this meant that the 4-nozzle and 5-nozzle designs would not be necessary. It was also decided between the process/end effector design team and the robot design team that for reasons of flexibility and convenience, each robot should have more than one nozzle. Thus the choice was narrowed to 2 or 3 nozzles, and the final decision remained unresolved until the end of the Process Optimization phase. On the basis of economics and paint removal rate alone, the 2-nozzle or 3-nozzle design would suffice. Two additional factors, however, pushed the final decision in the direction of the 3-nozzle design. First of all, when the end effector design had begun, it was determined that there was adequate space available for three blast nozzles. Secondly, it was decided that each nozzle would have its own blast hose and be turned on or off independently of the others. This feature enabled the 3-nozzle design to be far more flexible in its blast pattern than the 2-nozzle design (see Figures 4-1 and 4-2). Thus, the decision was finally made during end effector preliminary design to use the 3-nozzle approach.

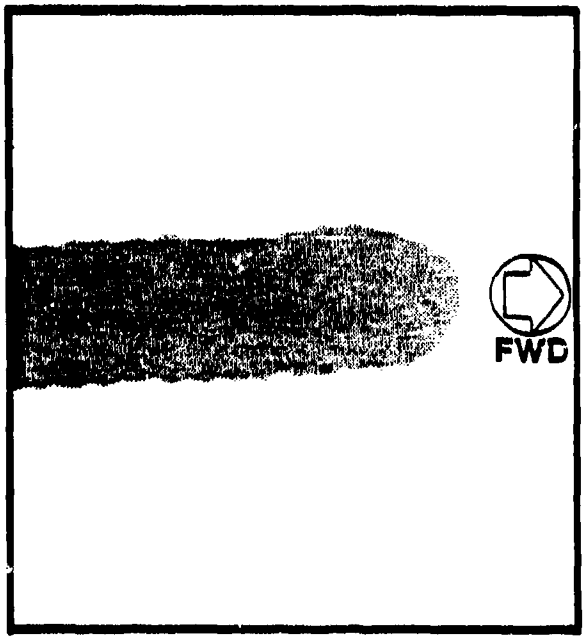
4.2 Nozzle Diameter

The industry "standard" for plastic media aircraft paint stripping is the "1/2-inch nozzle" so-called for the inner diameter of the constricted region. Nevertheless, there are some facilities which occasionally use a 1/4" or 3/8" nozzle for less aggressive treatment.

It was found from our Process Optimization tests in comparing the 1/4" nozzle with the 1/2" nozzle that the 1/2" nozzle conveyed more media at the same nozzle pressure and achieved higher paint removal rates. It was decided, therefore, six weeks into Process Optimization that it was no longer an issue and all further testing would be done with the 1/2" nozzle. Furthermore, unlike the decision regarding the number of nozzles, this was not an issue which would prevent the end effector design from going any

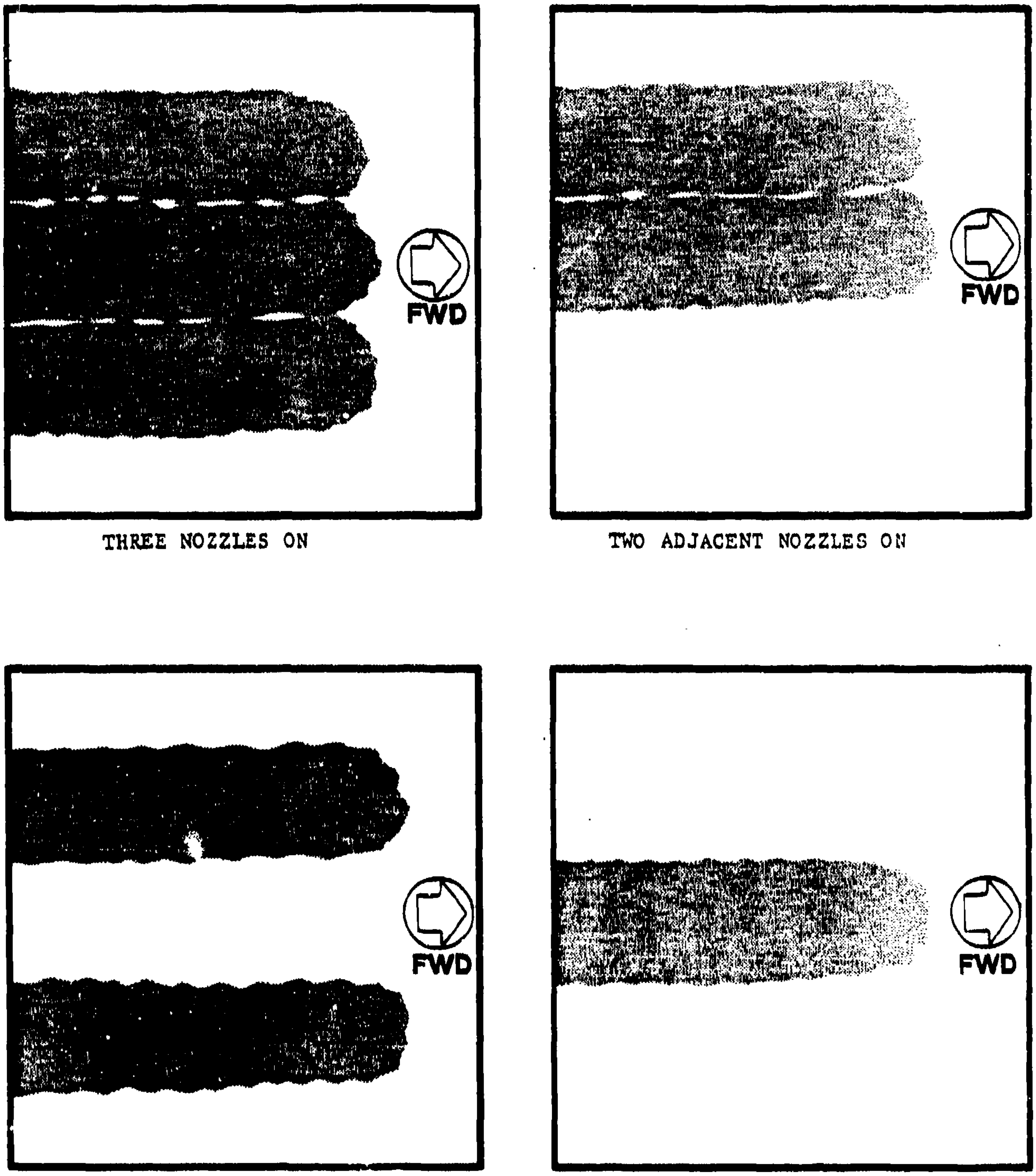


TWO NOZZLES ON



ONE NOZZLE ON

Figure 4-1. Blast Patterns of a Two-Nozzle End Effector



THREE NOZZLES ON

TWO ADJACENT NOZZLES ON

TWO NON-ADJACENT NOZZLES ON

ONE NOZZLE ON

Figure 4-2. Blast Patterns of a Three-Nozzle End Effector

further. Should it be decided later on to convert from 1/2" to 1/4" nozzles, that could be accomplished with only changes to be made in the process variables (e.g. stand-off and nozzle pressure), and not in the end effector design itself.

4.3 Nozzle Shape and Blast Pattern

The standard nozzle design for plastic media paint stripping is the single round nozzle with a round constricted region followed by a round, enlarged exit. Associated with this design is a characteristic blast stream that is conical in shape, concentrated in the center and diffused at the edges. The blast pattern is also characteristic, with the most intense blasting occurring in the center and diffused blasting occurring 360° around the center. The greatest amount of exposure to the blast media occurs in the middle of the swath, parallel to the direction of travel. The least exposure (and therefore the least effective stripping) occurs at the right and left edges. Depending upon the other process variables, either the middle is overexposed or the edges are underexposed in normal paint stripping operations.

It seemed to us early in the Process Optimization phase that if we could redistribute the blast pattern such that there was less in the center and more at the edges, we would have two beneficial results:

1) more uniform stripping, and

2) a wider swath width and therefore faster paint removal.

In our first attempt in this direction, we fabricated a blast nozzle from 1/2-inch copper tube and pinched the exit until it formed an oval approximately 1/8" wide and 3/4" long (see 1/22/87 in Appendix A). Good stripping rates were achieved (sometimes over 2.5 ft^2/min). However, the blast pattern was not significantly different than a straight round nozzle nor was the paint removal rate significantly better. More suitable blast patterns could probably be obtained with the proper nozzle design. This is a complex area, especially when dealing with two-phase flow (solid particles and compressible gas). Since the circular blast pattern provides acceptable results and can be produced with standard, off-the-shelf nozzles, we did not investigate special nozzle designs any further.

Our next step was to build a blast nozzle consisting of two 1/2-inch copper tubes, with a spacing of 2-3/4" between centers, joined to a single 1/2-inch copper tube which in turn is attached to the 1-1/2" blast hose (see Figures 4-3 and 4-4, Appendix A). The exits of the individual copper tubes were also pinched in order to obtain wider swaths from each. It is suspected, but not certain, that the pinching of the tubes did not have much effect. What was certain, however, and very useful was the indication that by overlapping two blast patterns where they are both diffused, a combined swath can be obtained that is sufficiently uniform and much wider than one blast stream alone. For example, a single nozzle at 25 PSI and 12" stand-off produced a swath width of 3-1/2" and a paint removal rate of

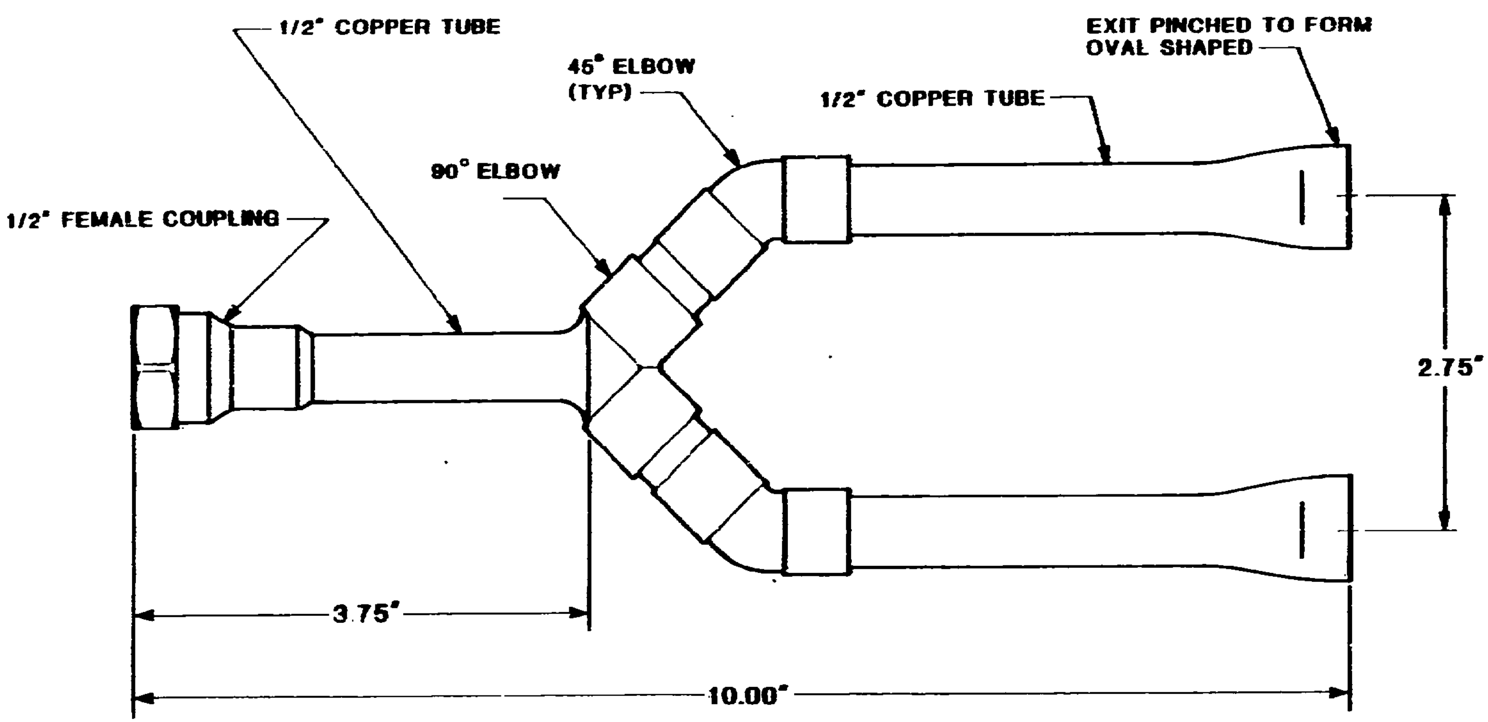


Figure 4-3 . Experimental Copper-Tube Dual Nozzle

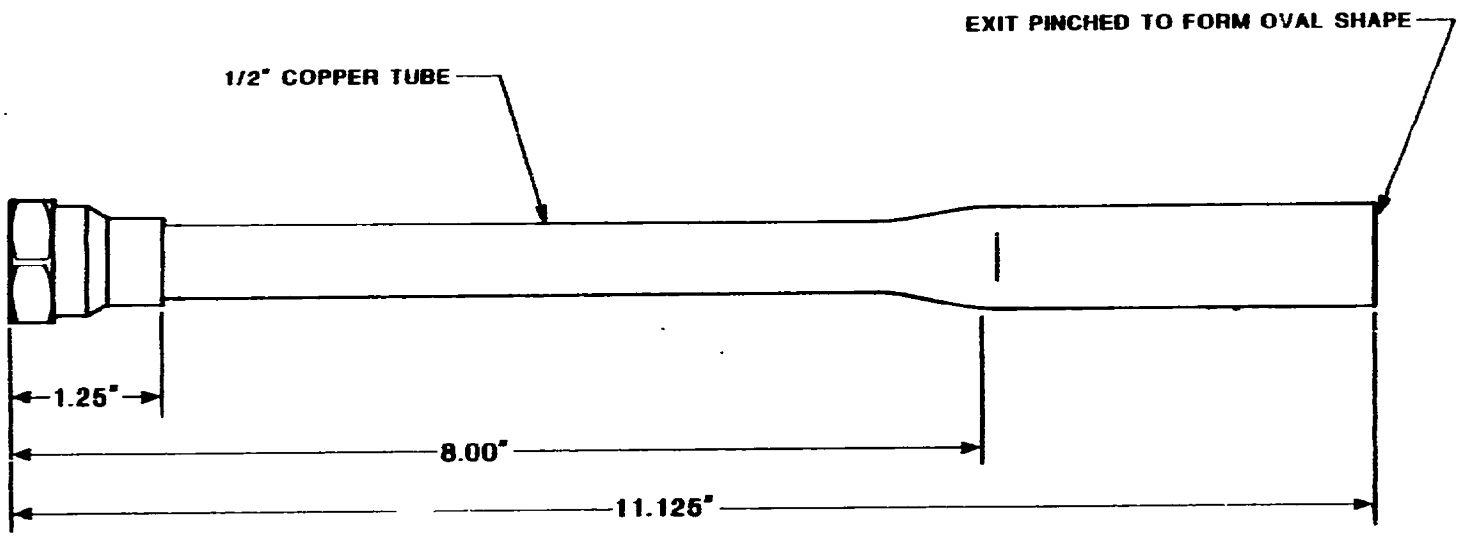


Figure 4-4. Experimental Copper-Tube Nozzle

0.85 ft^2/min. (see 2/12/87, Appendix A). Under almost identical conditions, a dual nozzle at 23 PSI and 12" stand-off produced a swath width of 5" and paint removal rate of 1.7 ft^2/min (see 1/27/87, Appendix A). From this it was concluded that it is advantageous and feasible to strip with two nozzles side-by-side instead of one. However, two limitations of this design were apparent:

1) The reason that the dual-nozzle swath was only 5" instead of twice the single nozzle swath width (3-1/2") was that the two nozzles had to share the compressed air and plastic media from the same blast hose.

2) Secondly, the two nozzles could not be controlled independently. We know, for example, that there will be locations on the aircraft when it will be better to blast with only one nozzle and focus the paint stripping effect on a narrower strip, for example, a decal. Moving closer to the aircraft in order to narrow the swath is not desirable because of the increased danger of colliding with the aircraft and because with the multi-nozzle system, it leaves an unstripped region between two well-stripped swaths. Changing pressures is a feasible method of handling decals, but that alone is not sufficient nor is it the easiest parameter to vary while the robot is in motion. With air-actuated solenoid valves, either of two independent blast nozzles could be shut off very quickly while the other continues its operation.

Upon this realization, we discontinued any further testing of the dual nozzle and came to the following conclusions:

1) The blast pattern of a pinched oval nozzle is not significantly wider than a round nozzle. For the little that is gained, it is better from a practical maintenance point-of-view to use standard, commercially-available 1/2" nozzles.

2) A wider swath and higher paint removal rate can be obtained by placing two nozzles side-by-side and allowing their blast patterns to overlap partially.

3) It is better to have nozzles with their own blast hoses which can be shut on and off independently of each other instead of two nozzles attached to the same blast hose and shut on and off by the same valve.

4) The RPSC shall have at least two nozzles mounted side-by-side each with its own blast hose. The blast pressure shall be measured, however, at the nozzles, and not only at the common source of compressed air.

A process design variable related to nozzle shape and blast pattern is the spacing between adjacent swaths. This has an effect on the spacing between adjacent nozzles and the spacing of subsequent paths in the robot

program. This issue was explored more fully in latter March 1987 and is addressed in Section 5.4, Swath Spacing.

One more attempt was made in late March 1987 to create a wider blast stream. This time narrow streams of compressed air were directed at the blast stream just beyond the exist of the blast nozzle while the robot was stripping paint (see 3/27/87, Appendix A) similar to methods used in spray painting equipment. The intention was that the air streams would redistribute the flow of plastic particles from the middle of the stream to the outside, thus creating a wider swath. This technique was entirely ineffective, probably because the momentum of rapidly traveling plastic particles is too great to allow a small (90 PSI) stream of air to change the direction of its velocity.

4.4 Plastic Media Sieve Size

The first blast system that was used in the Process Optimization tests was the Blast'n Vac system from Turco Products. It came with DuPont media, 30/40 sieve size and 3.5 mohs hardness. With the second and third systems, we used U.S. Technology Polyplus media, 3.5 mohs hardness and 20/30 sieve size. Satisfactory paint stripping results were achieved with both media and no obvious differences between the two were observed that could be accounted for by the difference in sieve size only. Identical conditions were not duplicated for both media. It was felt that further exploration of media sieve sizes had little more to add to the design of the Robotic Paint Stripper, and therefore, sieve size ceased to be an issue in Process Optimization. On the basis of our experience, the experiences of other researchers, and conversations with users, we arrived at the following conclusions:

1) Paint can be removed robotically at satisfactory rates using 30/40 or 20/30 sieve size media.

2) Like nozzle diameter, the RPSC will be able to adjust to different sieve sizes during operation by changing nozzle pressure, stand-off, or robot velocity. In fact, as new media becomes broken down, sieve size will change and the RPSC will have to adapt.

3) Our role with regard to sieve sizes is not to specify one sieve size and design the RPSC around it, but to make the RPSC flexible enough so that it can accommodate more than one sieve size. In face, many her factors besides RPSC design will determine what sieve sizes are used to strip military aircraft, including Air Force T.O., standard practice and personal preference of the facility, cost effectiveness, availability of the media, and the conclusions being drawn by plastic media paint stripping studies conducted by other contractors.

5.0 PROCESS DESIGN VARIABLES

5.1 Nozzle Angle

One of the purposes of the initial paint stripping tests was to compare the effects of various nozzle angles. Specifically, the following angles were chosen:

1) 90° (perpendicular to the surface)

2) 70° pitch (nozzle lowered by 20°)

3) 70° pitch/70° yaw (nozzle lowered by 20° and leaned to the left by 20°).

All three nozzle angles gave approximately the same results. The conclusion drawn from these tests was that paint removal effectiveness is not strongly influenced by a change in nozzle angle between 90° and 70°. The degree to which paint removal is affected beyond 70° was not investigated. It was observed, however, that when traveling over curved parts the angle between nozzle and substrate changed dramatically, and yet the paint was still removed. During the first month of Process Optimization tests, a trip was taken to Hill AFB, and one researcher spent a full work day blasting aircraft parts in the bead blast facility. Among his observations was the fact that widely varying angles (±60°) had almost no influence on paint removal effectiveness. It was the combination of these tests and experiences, together with consultation from the robot design team, that brought us to the following important conclusions:

1) A perpendicular orientation (90°) is the most effective for plastic media paint stripping, but not much better than 80° or 70°.

2) The RPSC robot shall be taught and programmed to follow a path over the aircraft that is perpendicular to the surface.

3) It is not necessary for the RPSC to measure the angle between the end effector and the aircraft and to readjust the angle of the end effector.

4) If a robot is programmed to blast at an average angle of 90°, any sudden change in contour of the aircraft will reduce that angle to something less than 90°. If the robot is programmed to blast at a shallower angle (e.g. 70°), some rapid changes in contour will reduce that angle below the level of paint removal effectiveness. Thus is was concluded that for a robotic situation, the nozzle should be oriented perpendicular to the surface.

5.2 Nozzle Stand-off Distance

As stand-off distance increases from very short to very long, paint removal rate starts out very low (because the swaths are too narrow), rises to a maximum, and falls back down again (because the blast is too weak). Thus there is an optimal intermediate stand-off distance which will produce the maximum paint removal rate. This optimum is dependent upon several other variables, but especially robot velocity, nozzle pressure, and the nature of the substrate and coating. In essence, anything that makes paint come off more easily will increase the optimal stand-off distance. This includes higher nozzle pressures, lower robot velocities, anodized aluminum surface, and coatings that are thin and aged. On the other hand, the conditions or parameters that reduce the optimal stand-off distance include lower nozzle pressures, higher robot velocities, alclad aluminum surface, and coatings that are thick and fresh. Table 5-1 gives a more complete listing of these trends.

TABLE 5-1. THE TREND OF OPTIMAL[1] STAND-OFF DISTANCE

Factors Which Increase the Optimal Stand-off Distance	Factors Which Decrease the Optimal Stand-off Distance
Higher nozzle pressures	Lower nozzle pressures
Lower robot velocities	Higher robot velocities
Anodized aluminum surface	Alclad aluminum surface
Thin and aged paint	Thick fresh paint
Perpendicular nozzle angle	Shallow nozzle angle
Larger nozzle diameter	Smaller nozzle diameter
Larger sieve size	Smaller sieve size
Harder plastic media	Softer plastic media

[1] "Optimal" as the word is used here is determined by the maximum paint removal rate.

In the military aircraft painting community, most paint stripping is performed at a nozzle stand-off distance of 16"-36". Very short stand-off distances (less than 6"), although it is the most aggressive approach and removes the paint within its swath the most quickly, bears with it the following disadvantages:

1) It demands of the paint stripping robot the most accuracy in stand-off positioning because of the increased possibility of collision with the aircraft.

2) It demands of the paint stripping robot the most accuracy in side-to-side positioning because if there is too much overlap of the swaths, overexposure occurs and if there is too little, a gap of unstripped paint is left behind.

3) The paint removal rate is sub-optimal because the swath is so narrow.

Very long stand-off distances (greater than 48"), although it is the safest in terms of potential substrate damage, carries with it the following disadvantages:

1) The actual paint removal ability is extremely diminished and requires very high nozzle pressures (greater than 60 PSI) or very slow robot velocities (less than 25 IPM).

2) The possibility of damage to the substrate due to foreign objects (i.e. sand or metal) in the plastic media is increased if high nozzle pressures are used.

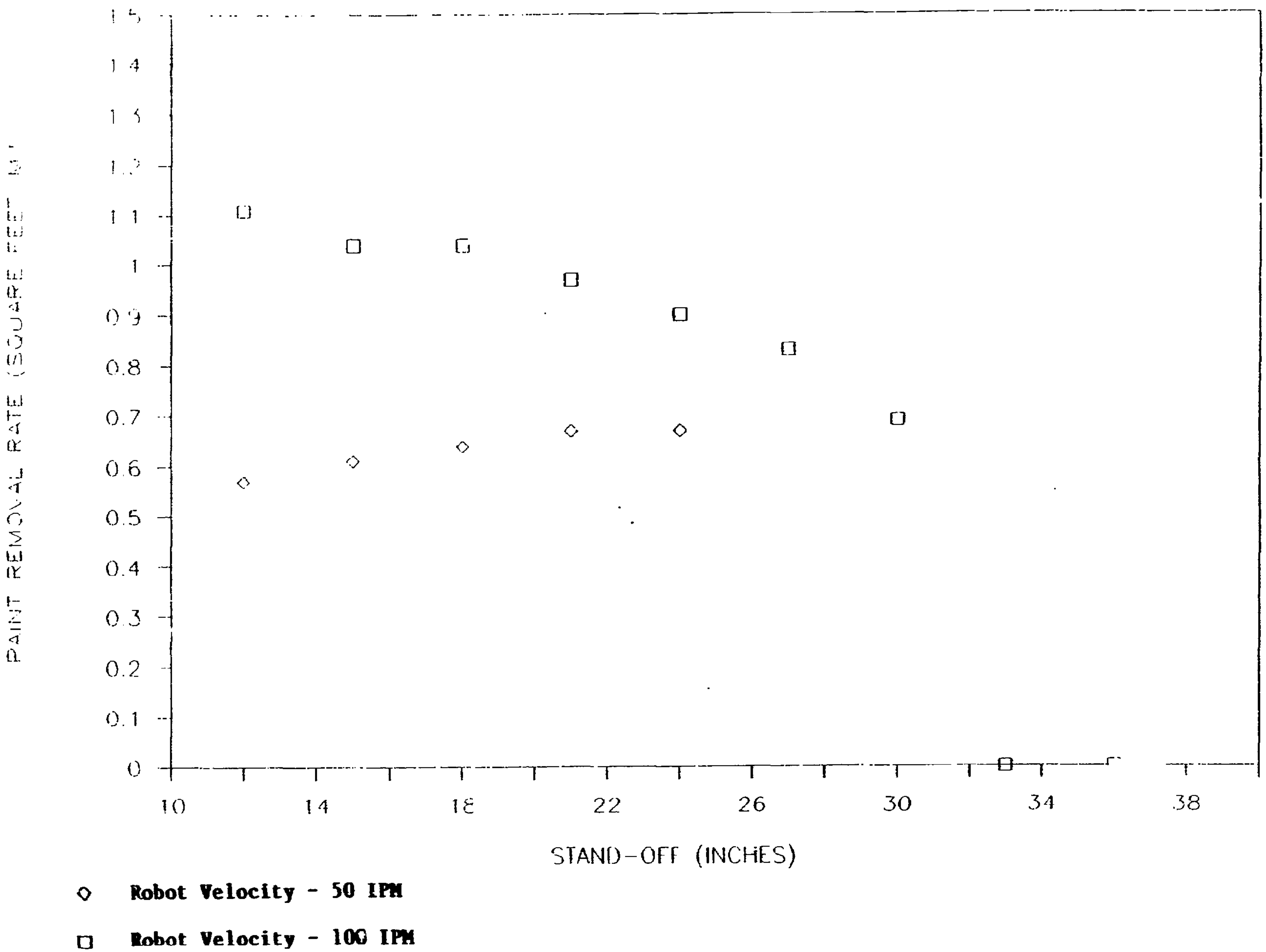
3) The overall paint removal rate is very low if low robot velocities are used.

4) Some areas of the aircraft will not be accessible from a stand-off distance of 48" (e.g. the underside of the aircraft).

The initial Process Optimization tests were performed with the Turco Blast 'n Vac system in the closed recovery mode because we did not yet have our blast room fully enclosed. We were limited therefore to stand-off distances of 5.5" and 3.25" determined by the length of the vacuum recovery brushes. The tests performed with the Autostripper and PMB-BV systems varied from 9" to 36" (see Figure 5-1). Generally speaking, for nozzle pressures between 20-30 PSI and robot velocities between 50-100 IPM, using a standard 1/2-inch nozzle blasting an F-4 turtleback, the optimal stand-off distance is somewhere between 12" and 24". For thin, aged paint on anodize surface, this could go up, and for alclad regions it could go down. Beyond 30", however, paint removal rate goes down quickly. Working in conjunction with the robot design team and software development team, it was decided that for ease of programming and safety of the aircraft, 24" stand-off would be preferable to a 12" stand-off. The tests showed us that a 24" stand-off was feasible for nozzle pressures of 10, 20, and 30 PSI and robot velocities between 25-200 IPM. It was found to be the optimal stand-off distance for a nozzle pressure of 20 PSI and a robot velocity of 50 IPM blasting an F-4 turtleback. It was also noted that very few military paint stripping facilities will use a stand-off shorter than 18", including Hill AFB and North Island NARF. Due to the concern over possible aircraft skin damage due to over-aggressive plastic media paint stripping, the trend is

Figure 5-1

NOZZLE STAND-OFF OPTIMIZATION



toward longer stand-off distances. Furthermore, A.F.T.O. 1F-4C-3-1-6 which stipulates the conditions required for plastic media stripping of F-4's, requires that a stand-off of 24"-48" be maintained while stripping fiberglass and aluminum sections of the F-4. So, without going through a structured and comprehensive test plan, it was decided by the Process Optimization team after performing several optimization tests at a 12" stand-off to perform the remainder at 24" and adopt this stand-off as the standard for the RPSC. Despite the adoption of a 24" stand-off, the robot and end effector were designed with the flexibility of being able to accommodate any stand-off distance up to the limits of the bead blast facility.

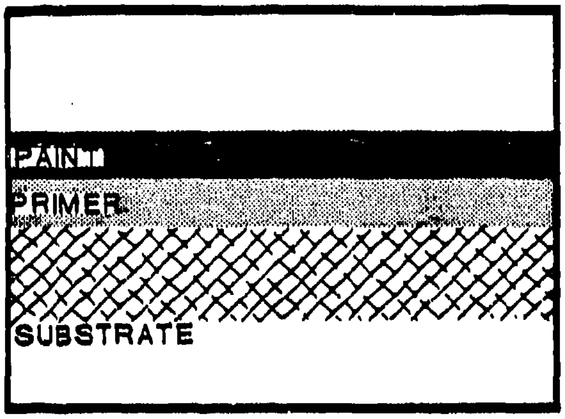
The nozzle stand-off optimization tests provided an insight into the mechanism of plastic media paint removal. Nozzle stand-off was the only parameter that was varied continuously instead of in discrete steps; thus, when the coat of primer which could not be removed at 33" was removed at 30", it became clear that not only was the upper surface of the coatings being eroded, but the primer/substrate bond was also being progressively broken down (see Figure 5-2). Somewhere between 33" and 30" it crossed over that threshold by destroying the bond and breaking the loosened primer away from the neighboring primer.

In contrast with this impact/abrasion mechanism, there are those situations where the bond is not broken down, and instead the paint and primer is eroded only from the surface (see Figure 5-3). Whether a coating is removed by erosion only or by erosion and impact depends almost entirely on the nature of the substrate and coatings.

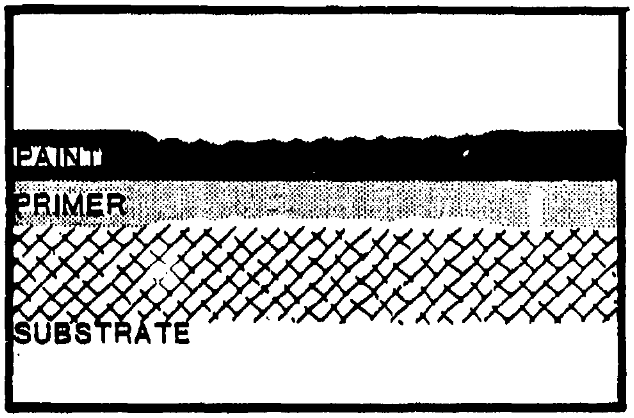
Perhaps the most important implication of this distinction of mechanisms is this: if the RPSC is unable to strip paint from delicate substrate at an assigned pressure and it is suspected from its appearance that the paint is being loosed by impact mechanism, the a small increase in pressure may provide significant improvement in paint removal rate. If it is obvious that the bond is strong and the coating is being removed by erosion only, then a small increase in pressure will provide only slight improvement in the stripping rate.

5.3 Plastic Media Mass Flow Rate

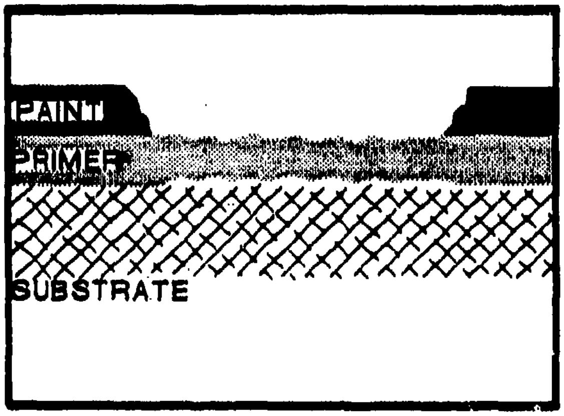
Among industrial and military plastic media paint strippers, very little is known about plastic media mass flow rates. Most facilities will know how much media is lost for bookkeeping purposes, but few actually know how much is flowing through the blast hose during a paint-strip operation. Until recently, it has not been an issue of concern and little or no attempt has been made to measure it or optimize it. In the extensive military literature on plastic media aircraft paint stripping, nothing was stated about the relationship between mass flow rate and paint removal rates. Some manufacturers' blast equipment do not even have a plastic media valve that is adjustable to vary the amount of mass flow. Therefore, we had no previous assumptions with regard to mass flow, except for the logical argument that if a certain amount of media possesses a certain amount of kinetic energy with which to perform work on aircraft coatings,



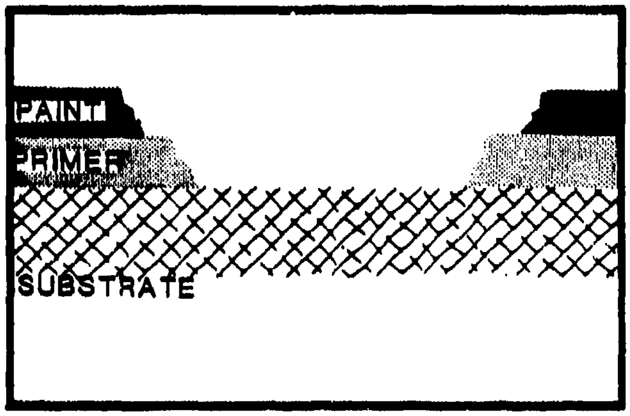
UNSTRIPPED SURFACE



SLIGHTLY AGGRESSIVE; SAME ABRASION OF PAINT; SAME BREAKDOWN OF PRIMER BOND.

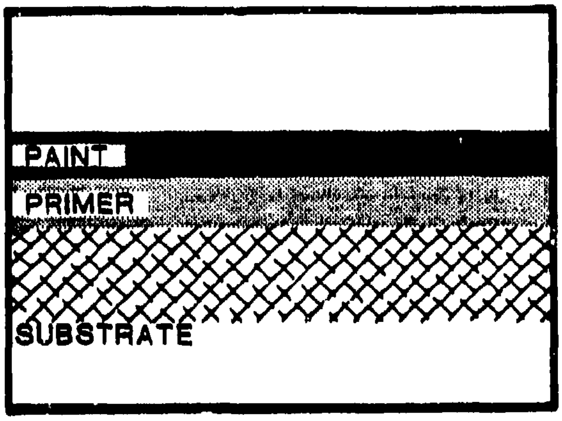


MODERATELY AGGRESSIVE; TOTAL ABRASIVE REMOVAL OF PAINT: ALMOST TOTAL BREAKDOWN OF PRIMER BOND.



SLIGHTLY BEYOND THRESHOLD; LOOSENED PRIMER HAS BEEN TORN FROM SURROUNDING PRIMER.

Figure 5-2. Removal of Coatings by Impact Effect and the Destruction of the Primer/Substrate Bond



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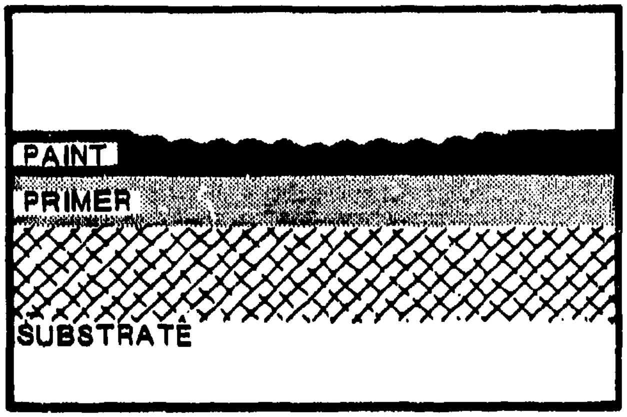
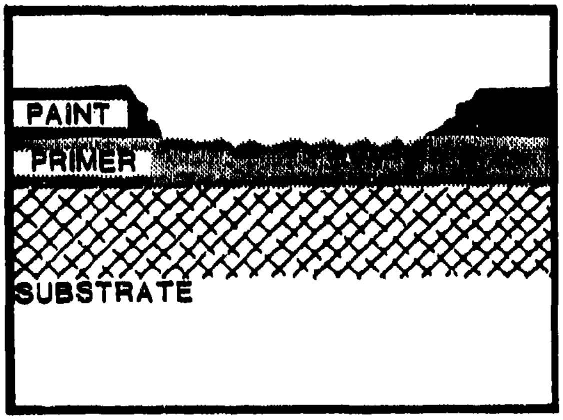
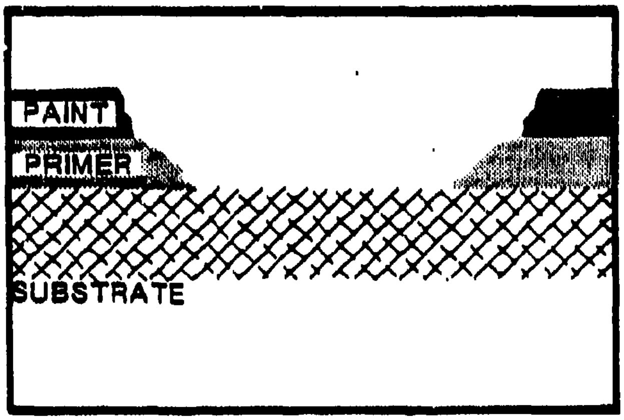


SLIGHTLY AGGRESSIVE; SAME ABRASION OF PAINT



MODERATELY AGGRESSIVE; TOTAL ABRASIVE REMOVAL OF PAINT; SAME ABRASIVE REMOVAL OF PRIMER



EXTREMELY AGGRESSIVE; TOTAL ABRASIVE REMOVAL OF PAINT AND PRIMER

Figure 5-3. Removal of Coatings by Abrasive Effect

then a little more media would provide a little more energy to perform paint removal a little more quickly.

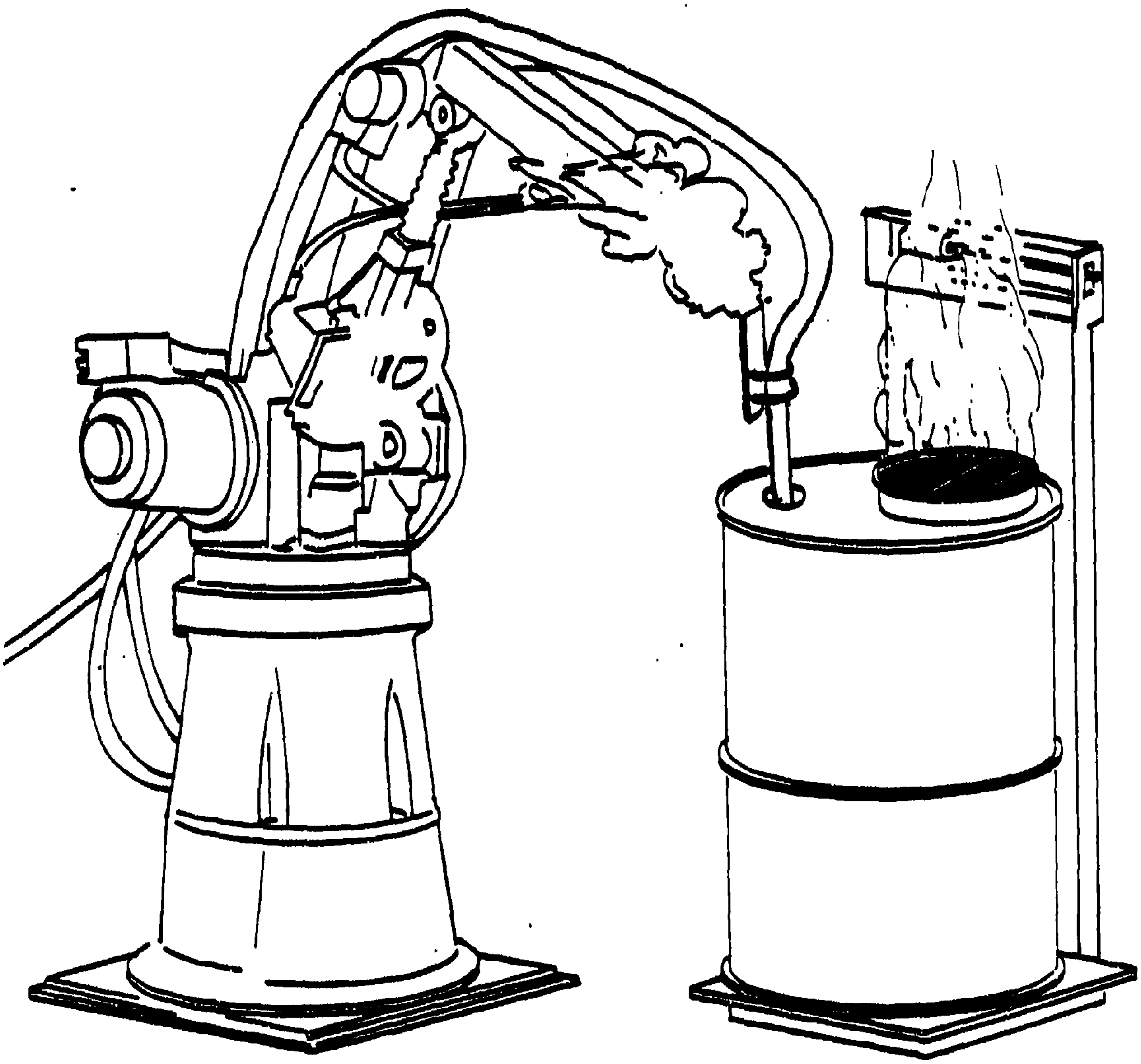
In mid-March 1987, we measured the mass flow rate as a function of nozzle pressure and valve position (see Appendix A, 3/18/87). The robot held the blast nozzle inside a 55-gallon steel drum with a steel mesh filter and vent (see Figure 5-4). We used the Schmidt PMB-BV blast system, which had a Thompson valve that allowed media to fall from the pressurized blast pot into the blast hose where it was caught by the stream of compressed air and transported to the nozzle. It took 10 turns of the threaded valve cover to go from fully closed to fully open. For each turn of that valve, the mass flow for one minute was recorded. That data is shown in Appendix A, 3/18/87, and the data is shown graphically in Figures 5-5 to 5-7.

The first thing that we noticed in taking mass flow data was that no mass was flowing at 1, 2, or 3 turns of the valve. Apparently the slide gate in the valve had not yet created an opening to allow the passage of media. The second thing we noticed, as would be expected, was that as the valve was opened, more media flowed out. In fact, between 4 and 7 turns of the valve, the increase was roughly proportional to the opening of the valve. Between 7 and 10 turns, however, (which is also 70% to 100% full opening of the valve) curious inconsistencies occurred. At 10 PSI, for example, 7 turns of the Thompson valve gave a higher mass flow rate than 8 turns. We suspect that at this upper range, some measurement error occurred such as the escape of media. It could also have been that some complex phenomenon was occurring between the valve and blast hose that created this inconsistency. It was certain, however, that at each nozzle pressure (10 PSI, 20 PSI, and 30 PSI) an opening of 7 turns consistently produced a mass flow above all smaller valve openings.

In observing the sound produced by the flow of plastic media, we noticed a loud rushing sound of air and plastic at 20 and 30 PSI and a much more subdued sound at 10 PSI. Furthermore, the mass flow was higher at 10 PSI than at 30 or 30 PSI. Apparently, at 20 and 30 PSI, the media was carried and suspended by the airstream in what is called a dilute phase condition. At 10 PSI, however, the media was no longer suspended, but rather pushed as a solid mass in a dense phase condition. The dilute phase condition is similar to that used in the soundblasting industry and produces a powerful blasting effect because of the significant velocity of the particles. The dense phase transport, however, provides very little blasting effect and in fact is used by the material handling industry to pneumatically transport dry powdered and granular material.

In addition to dense phase occurring at 10 PSI, it was also observed that at 7 turns (70% of full open), the mass flow at 20 PSI is less than that at 30 PSI. There are at least three reasons why these two observations are important:

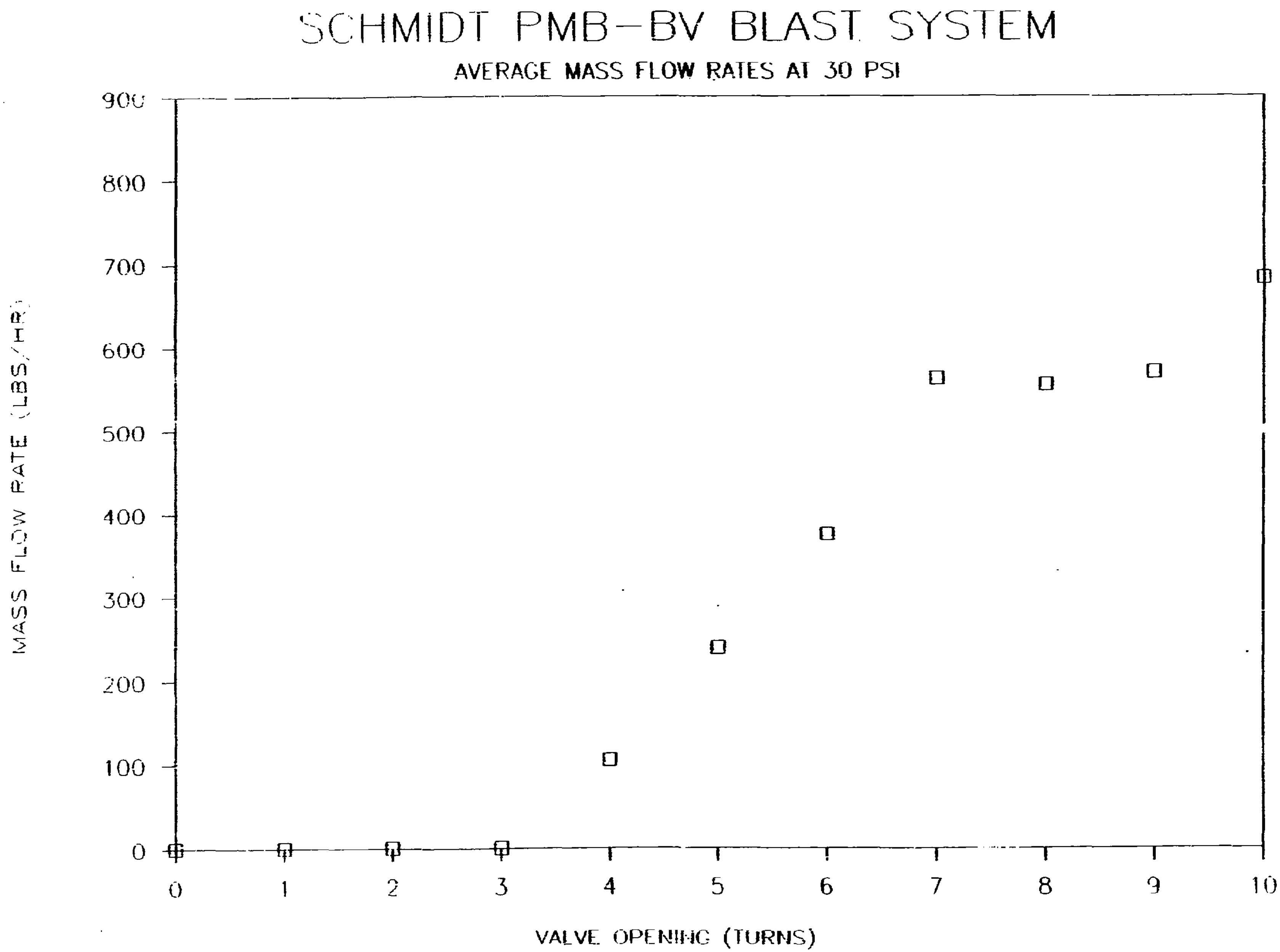
1) Although 10 PSI and 20 PSI are only 10 PSI apart, the apparent difference in the transport mechanism creates a distinct difference in the aggressiveness of the media. While 20 PSI may be



LAB SET-UP FOR PLASTIC MEDIA MASS FLOW MEASUREMENTS

Figure 5-4

Figure 5-5



SCHMIDT PMB-BV BLAST SYSTEM
AVERAGE MASS FLOW RATES AT 30 PSI
MASS FLOW RATE (LBS/HR)
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
VALVE OPENING (TURNS)

Figure 5-6

SCHMIDT PMB-BV BLAST SYSTEM

AVERAGE MASS FLOW RATES AT 20 PSI

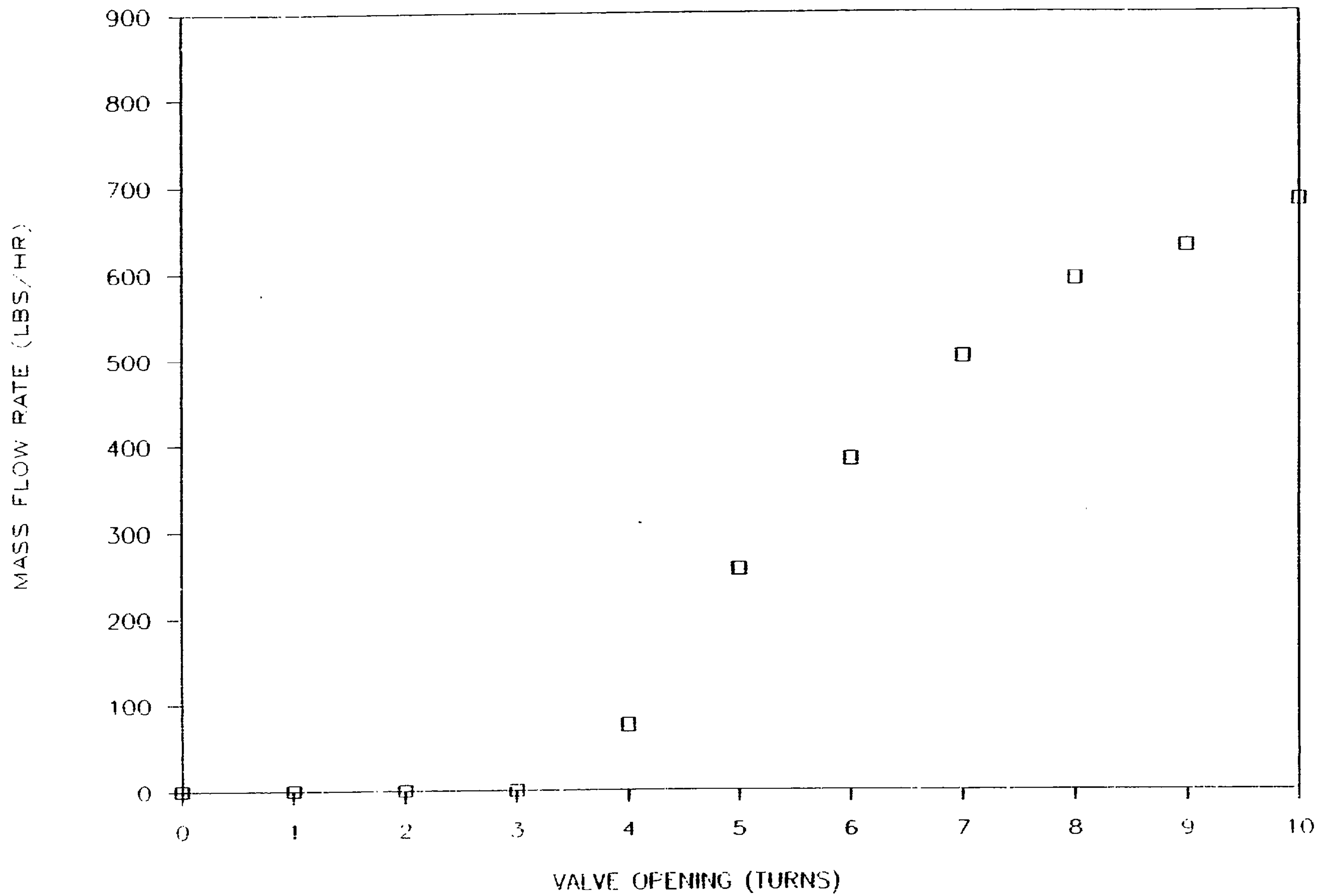
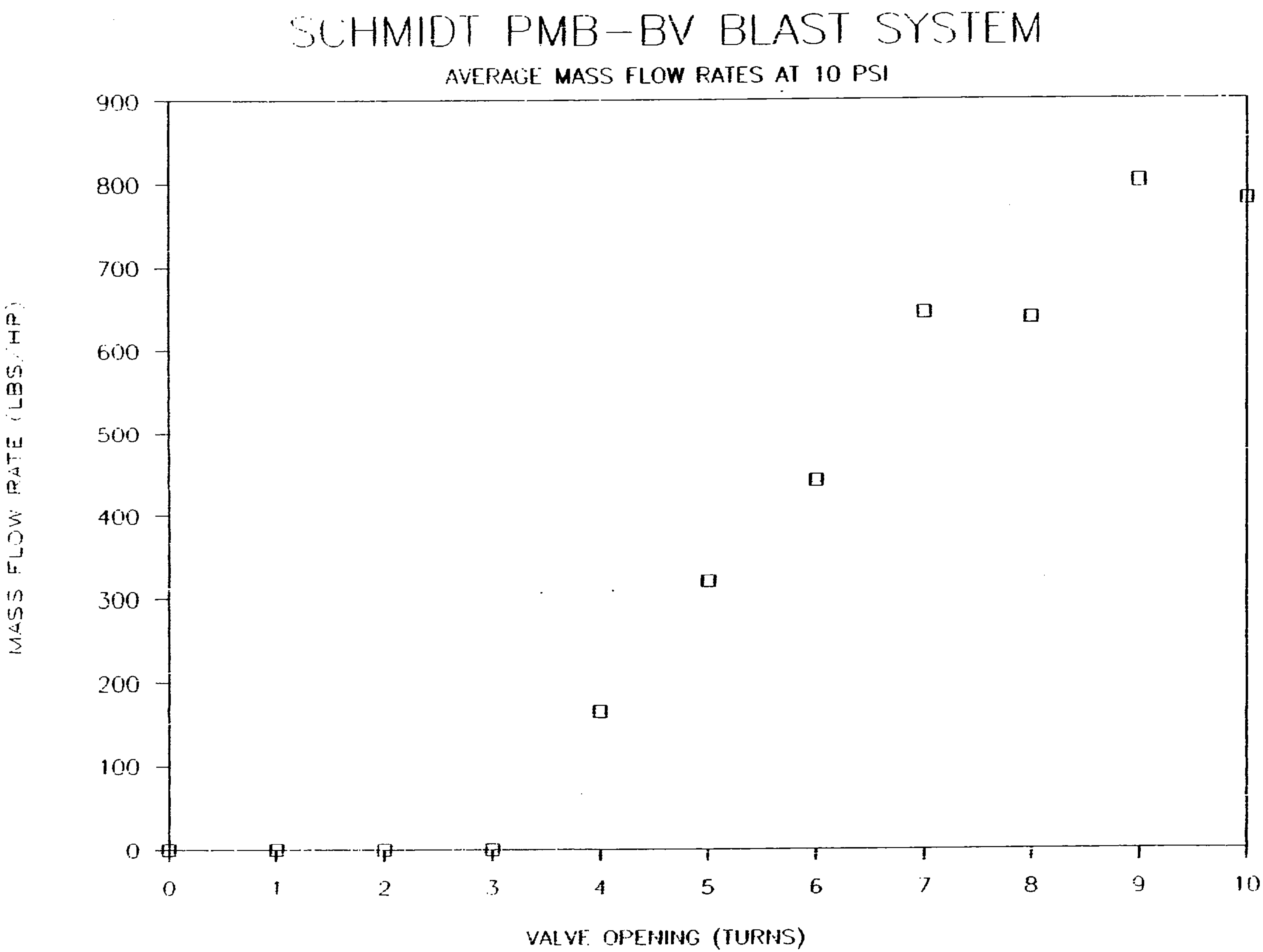


Figure 5-7


SCHMIDT PMB-BV BLAST SYSTEM
AVERAGE MASS FLOW RATES AT 10 PSI
MASS FLOW RATE (LBS/HR)
900
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
VALVE OPENING (TURNS)

preferable for rapid paint removal on durable substrate such as aluminum, 10 PSI may be preferred for more delicate substrate or even for the pneumatic transport of the media from the hoppers to the robot.

2) If media recirculation and consumption is an issue of economic concern, then it would be desirable to save on energy and material costs without sacrificing paint removal effectiveness or protection of the substrate. At seven turns of the media valve, because the mass flow is actually lower at 20 PSI than at 10 PSI or 30 PSI, there is a potential savings in operating at 20 PSI.

3) Seven turns of the Thompson valve represents the upper end of the linear region of mass flow vs. valve opening. Above seven turns, the media flow starts to enter dense phase.

A series of tests were conducted to measure paint removal rate vs. media mass flow rate (see Figure 5-8). It was fairly well established by this time that 20 and 30 PSI were the most useful nozzle pressures and 5, 6, 7 and 8 turns were the most useful valve openings. We chose robot velocities of 50 IPM and 100 IPM from previous experience. An opening of 7 turns consistently produced the highest paint removal rate. This was the final confirmation that was necessary to arrive at the following conclusions:

1) Seven turns of the media valve produces higher paint removal rates than any other valve opening.

2) Seven turns and 20 PSI provide the flexibility of being able to blast less aggressively while conserving on plastic media.

3) Seven turns and 10 PSI provide the flexibility of blasting in dense phase with a significantly higher mass flow providing acceptable paint removal rates for delicate substrates.

4) Seven turns of the Thompson valve shall be the standard valve opening for all future Process Optimization tests.

5) Mass flow rates at seven turns shall be the rates used for the design of the material handling system. Those rates are shown below in Table 5-2.

Figure 5-8

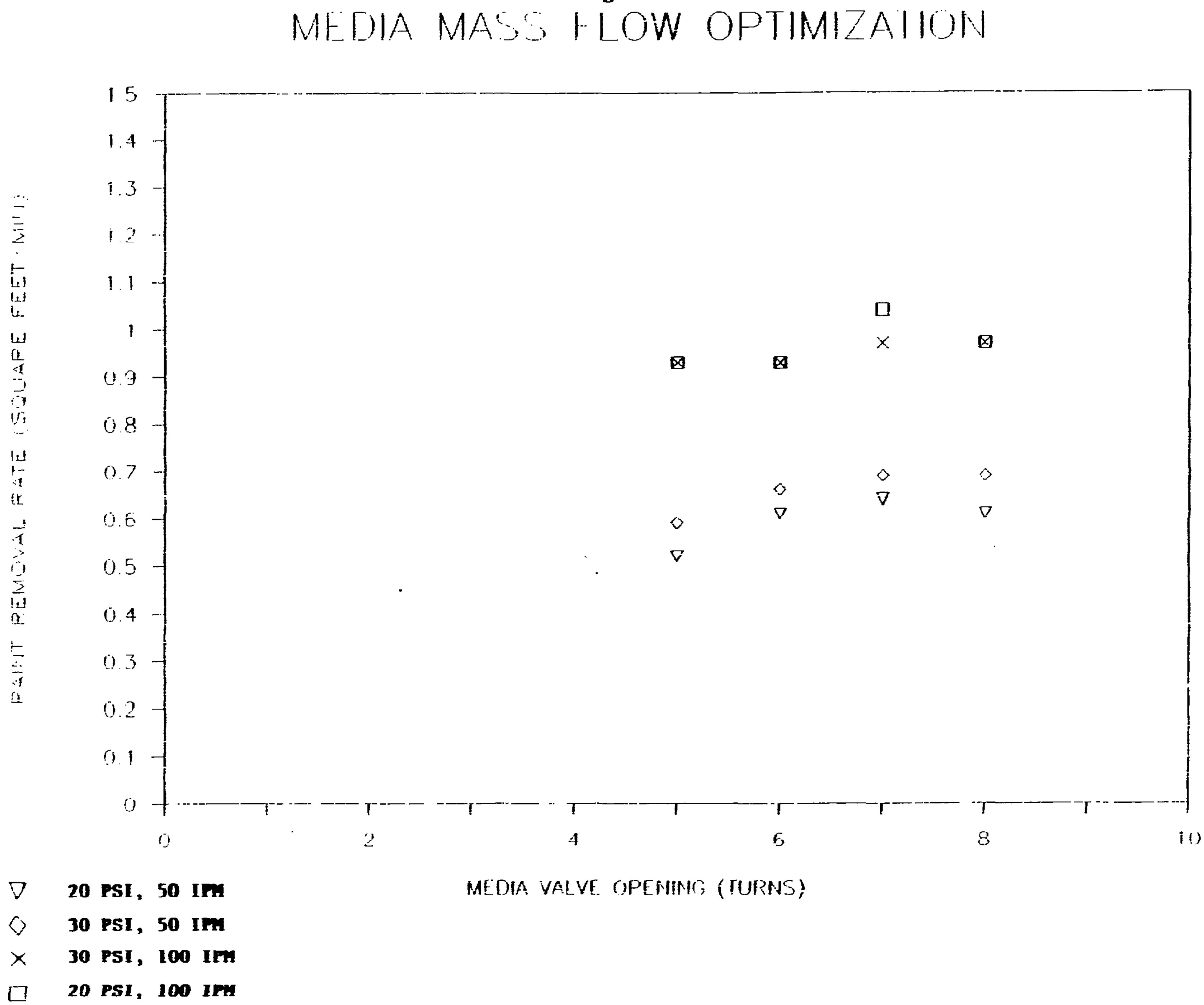

MEDIA MASS FLOW OPTIMIZATION
PAINT REMOVAL RATE (SQUARE FEET/MIN)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
MEDIA VALVE OPENING (TURNS)
▽ 20 PSI, 50 IPM
◇ 30 PSI, 50 IPM
× 30 PSI, 100 IPM
□ 20 PSI, 100 IPM

TABLE 5-2. MEDIA MASS FLOW FOR ONE NOZZLE AT 70% OPENING OF THE THOMPSON VALVE

Nozzle Pressure	Mass Flow Rate
10 PSI	641 lbs/hr
20 PSI	502 lbs/hr
30 PSI	562 lbs/hr

5.4 Swath Spacing

For effective and economical paint stripping, it is important that the swath spacing, or distance from center of one robot path to the next be made optimal. If the spacing is too small, excessive overlap will occur which will cause overexposure of the substrate and a reduction in robot productivity. If the spacings are too far apart, unremoved paint will be left between the swaths.

We found what we believed to be the optimal swath spacing for our unique conditions. We had picked a swath spacing of 2-1/2" quite arbitrarily for stripping F-4 turtlebacks (see Figure 5-9). Our other parameters were set as follows:

Nozzle pressure - 30 PSI
Mass flow - 7 turns of the Thompson valve
Stand-off - 24"
Robot velocity - 50-100 IPM

The width of a single swath under these conditions was found to be 1.90" with borders of primer 0.7" wide on either side (see Figure 5-10). It was observed that with a spacing of 2-1/2", a strip of paint approximately 1/2" wide was left between swaths. So we reduced the swath spacing by 1/4" assuming that 1/4" on each side would eliminate the 1/2" gap. We were right. This seemed to be a convenient and reasonable swath width, and so we adopted it as our standard. In working with the robot and software design teams, we decided it would be far more convenient and feasible to change robot velocity or nozzle pressure "on the fly" than to change swath spacing, as swath spacing would require reprogramming and reteaching of the entire robot path. This information became important in the design of the end effector for determining the minimum distance required between adjacent nozzles. Swath spacing was no longer an issue in Process Optimization and we arrived at the following conclusions:

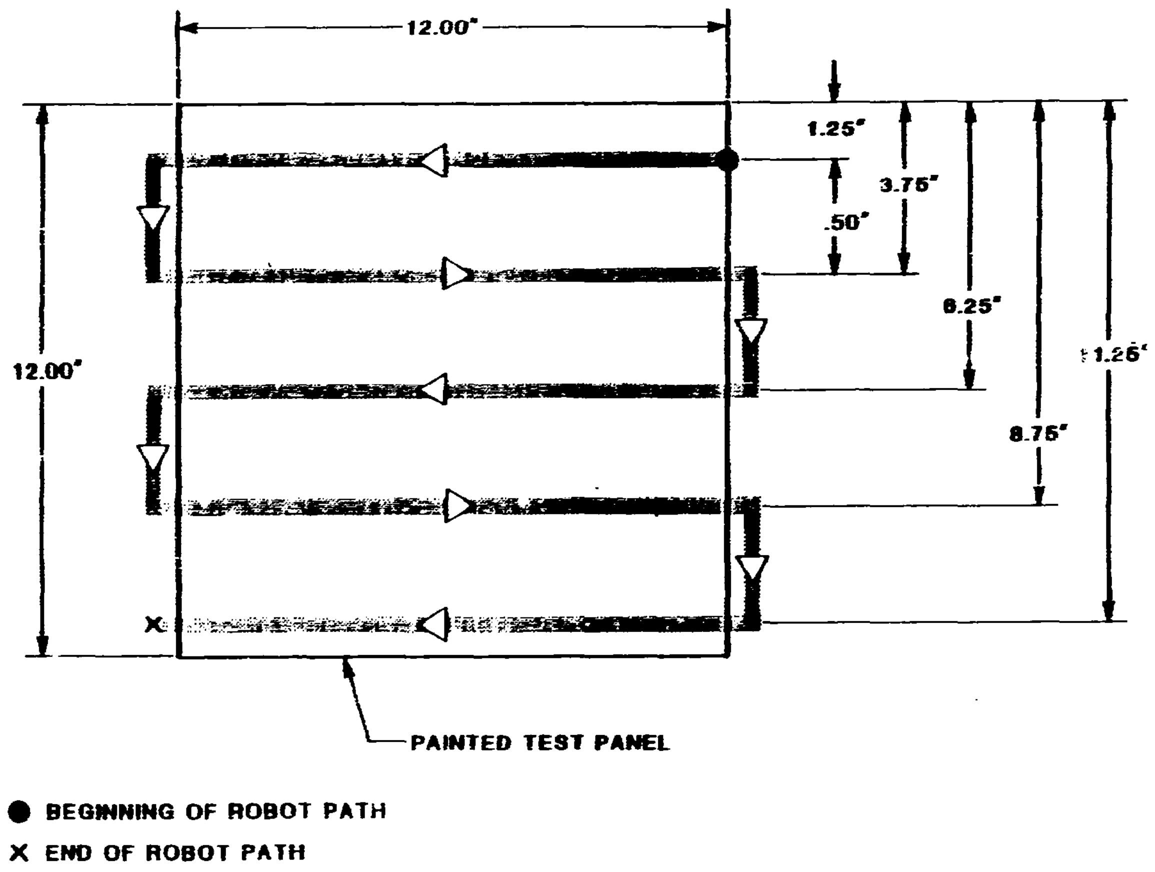
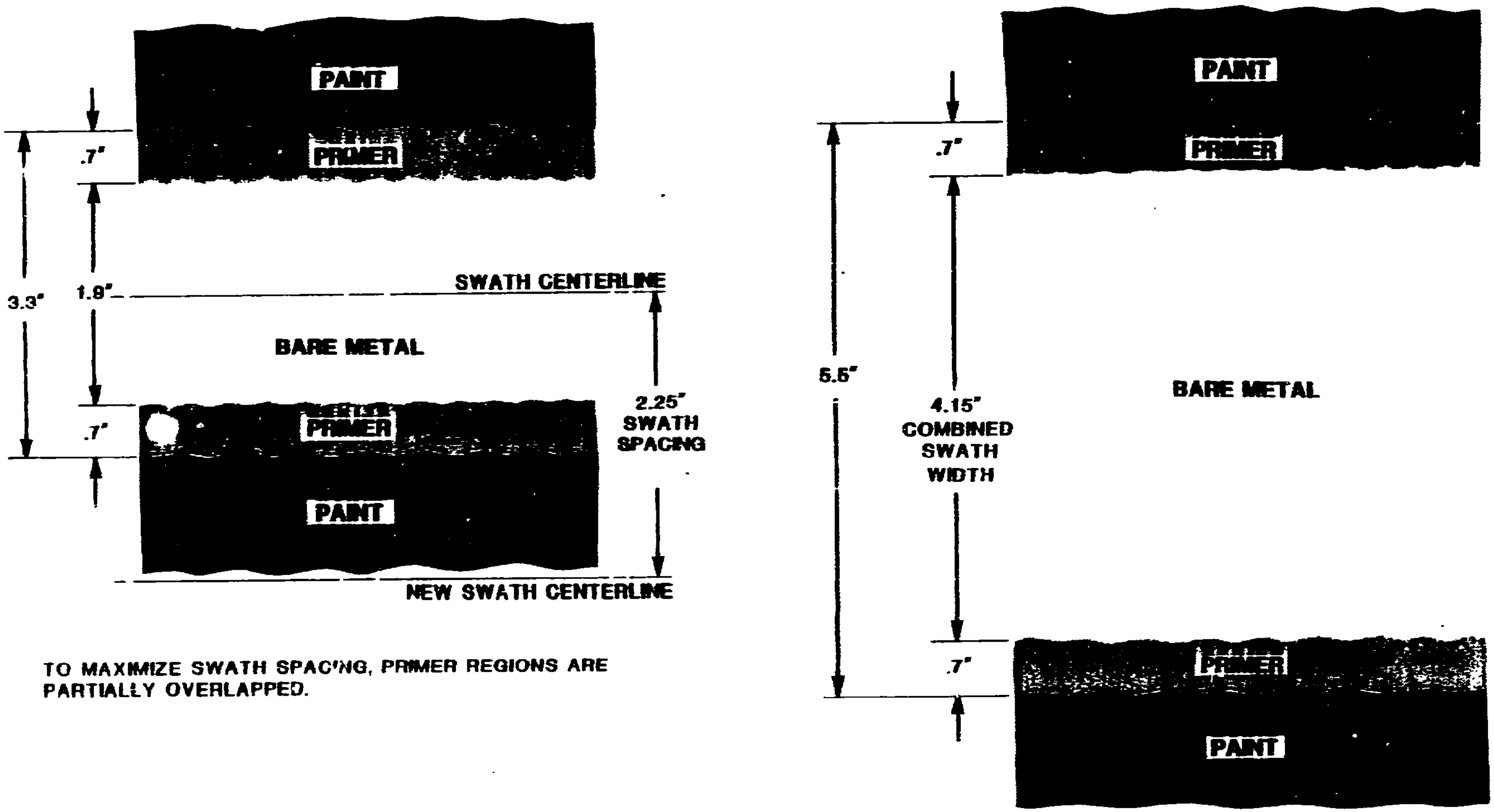


Figure 5-9. Robot Paint Stripping Path



TO MAXIMIZE SWATH SPAC'NG, PRIMER REGIONS ARE PARTIALLY OVERLAPPED.

NEW COMBINED SWATH WIDTH IS WIDER THAN THE SUM OF TWO INDIVIDUAL SWATHS.

Figure 5-10

OPTIMIZATION OF SWATH SPACING

1) The standard swath spacing for the RPSC design shall be 2-1/4".

2) Swath spacing is not a process variable that we would want to adjust "on the fly" during paint removal operation.

3) It may be necessary to adjust swath spacing between aircraft or between sections of the aircraft. Therefore, the distance between adjacent nozzles shall remain adjustable.

5.5 Nozzle Pressure

The most controversial of all process parameters, and at the same time the one variable that affects paint removal rate and potential substrate damage most dramatically, is nozzle pressure. There is a great deal of data recorded on this parameter, and as shown in Table 2-1, most military aircraft paint stripping is performed between 20-45 PSI, with the lower pressures usually used for fiberglass and graphite composites, and the higher pressures used for aluminum.

We took the existing data into consideration but felt confident that because of the consistency of robot control, 10 PSI would also be a feasible blast pressure. Thus we kept our blast pressures within the range of 10-40 PSI. We discovered very quickly that a 30 PSI blast pressure under robotic manipulation produces very thorough and very efficient paint removal effect for the three most common substrates: anodized aluminum, alclad aluminum, and graphite composite. Thus we dropped 40 PSI and did all testing between 10-30 PSI.

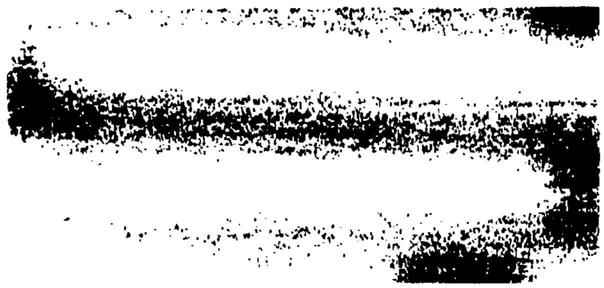
In order to compare the effects of various nozzle pressures, we stripped three (3) identical sections of a graphite composite panel at 10, 20, and 30 PSI. Figure 5-11 shows the photographs of three panels stripped at similar robot velocities, and Table 5-3 lists the maximum paint removal rate achieved at each nozzle pressure.

TABLE 5-3. OPTIMIZATION OF NOZZLE PRESSURE ON GRAPHITE COMPOSITE SUBSTRATE

NOZZLE PRESSURE	ROBOT VELOCITY	PAINT REMOVAL RATE
10 PSI	25 IPM	0.31 FT^2/MIN
20 PSI	75 IPM	1.29 FT^2/MIN
30 PSI	100 IPM	1.59 FT^2/MIN

Figure 5-11

OPTIMIZATION OF NOZZLE PRESSURE



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87

Graphite Composite Panel, 8-Ply
10 PSI, 50 IPM, 442 lbs/hr

PLASTIC MEDIA PAINT-STRIPPING, 3/26/87

Graphite Composite Panel, 8-Ply
20 PSI, 100 IPM, 502 lbs/hr

PLASTIC MEDIA PAINT-STRIPPING, 3/26/87

Graphite Composite Panel, 8-Ply
30 PSI, 100 IPM, 562 lbs/hr

The maximum paint removal rate was achieved at 30 PSI. The disadvantage in blasting at this pressure, however, is the greater danger of damaging delicate substrate. This was demonstrated in the series of tests mentioned above. In each test, the blast stream was turned on while the robot was approaching the test panel. The robot paused for just a moment (perhaps 1-2 seconds) before it began traveling at the assigned robot velocity. This is the one moment when the risk of damage is the greatest. Photomicrographs revealed, in fact, that at 30 PSI several fibers were broken. These photos are shown in Figure 5-12. At 10 and 20 PSI, there was no evidence of fiber damage.

Thus, we arrived at the following conclusions with regard to nozzle pressure:

1) A high nozzle pressure of 30 PSI removes paint very completely and efficiently at satisfactory rates on anodized aluminum, alclad aluminum, and graphite composite.

2) A nozzle pressure of 20 PSI, while less efficient than 30 PSI, also removed paint at satisfactory rates and is safer in terms of possible substrate damage.

3) A nozzle pressure of 10 PSI removes paint very slowly and is only acceptable when concern over the possibility of substrate damage will not allow 20 or 30 PSI.

4) It is important that while stripping an aircraft (whether manual or robotic), the end effector must always be in motion while the blast stream is directed against the aircraft, especially when blasting delicate substrate.

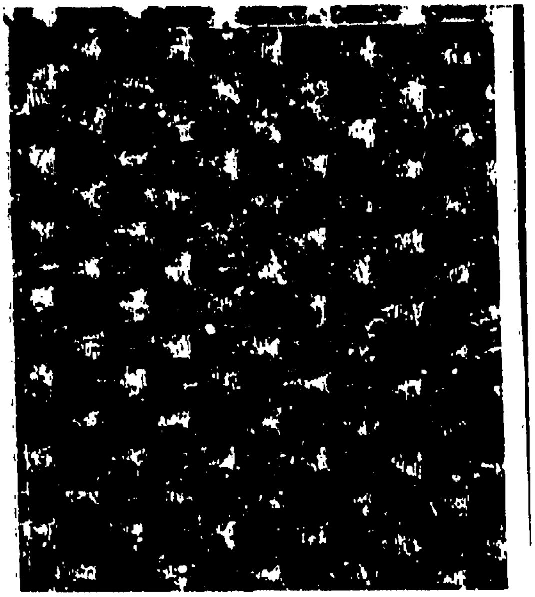
5) A nozzle pressure of 30 PSI is to be used for aluminum substrates and 20 PSI for composites. The RPSC is to be designed, however, with the flexibility of blasting at any pressure between 10 PSI and 100 PSI.

5.6 Robot Velocity

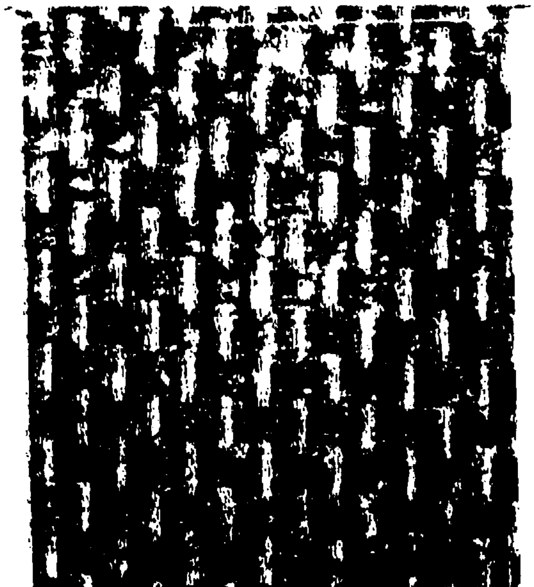
Prior to the RPSC project, there was no published data available with regard to the appropriate robot velocities to be used for automated aircraft paint stripping. We were given estimates, however, from some military facilities on the range of velocity at which their operators move the blast nozzles over the aircraft when stripping paint. The following table is a listing of those estimates:

Figure 5-12

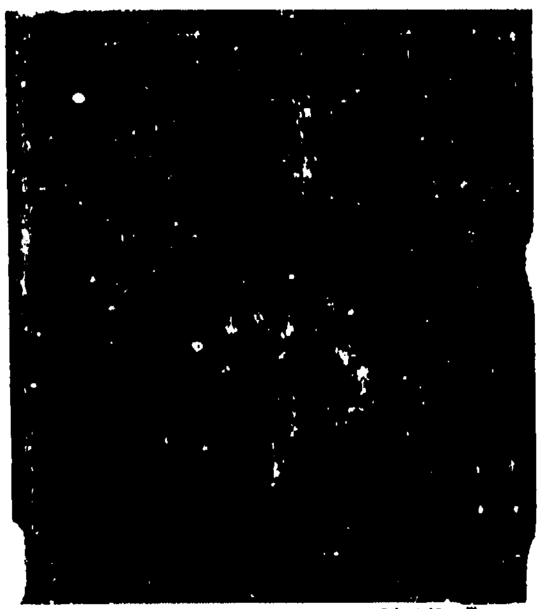
GRAPHITE COMPOSITE DAMAGE DUE TO PLASTIC MEDIA OVEREXPOSURE



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
30 PSI, 150 IPM, 562 lbs/hr, MAG: 13X



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
30 PSI, 100 IPM, 562 lbs/hr, MAG: 13X



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply, MAG:13X
30 PSI, 562 lbs/hr, robot stationary

TABLE 5-4. ESTIMATED BLAST NOZZLE TRAVEL RATES

FACILITY	BLAST NOZZLE TRAVEL RATE
Hill Air Force Base	18-72 IPM
Corpus Christi Army Depot	60-120 IPM
North Island NARF	Maximum Possible

The USAF Technical Order 1F-4C-3-1-6 which contains the instructions for plastic media paint stripping of F-4's addresses nozzle travel rate from the perspective of dwell time. The T.O. states that dwell time should be "minimum necessary to remove paint."

In other words, after stand-off and nozzle pressure have been specified, the operator is to move the nozzle as quickly as possible while still being able to remove the paint. This is the approach we took with the Process Optimization tests. Robot velocity is the one variable that is most easily optimized and adjusted. The other variables were normally chosen first, and then we looked for the highest robot velocity within the limits of 25-100 IPM that would give us adequate paint removal (see Appendix B, Parametric Boundaries for Acceptable Paint Removal Rates).

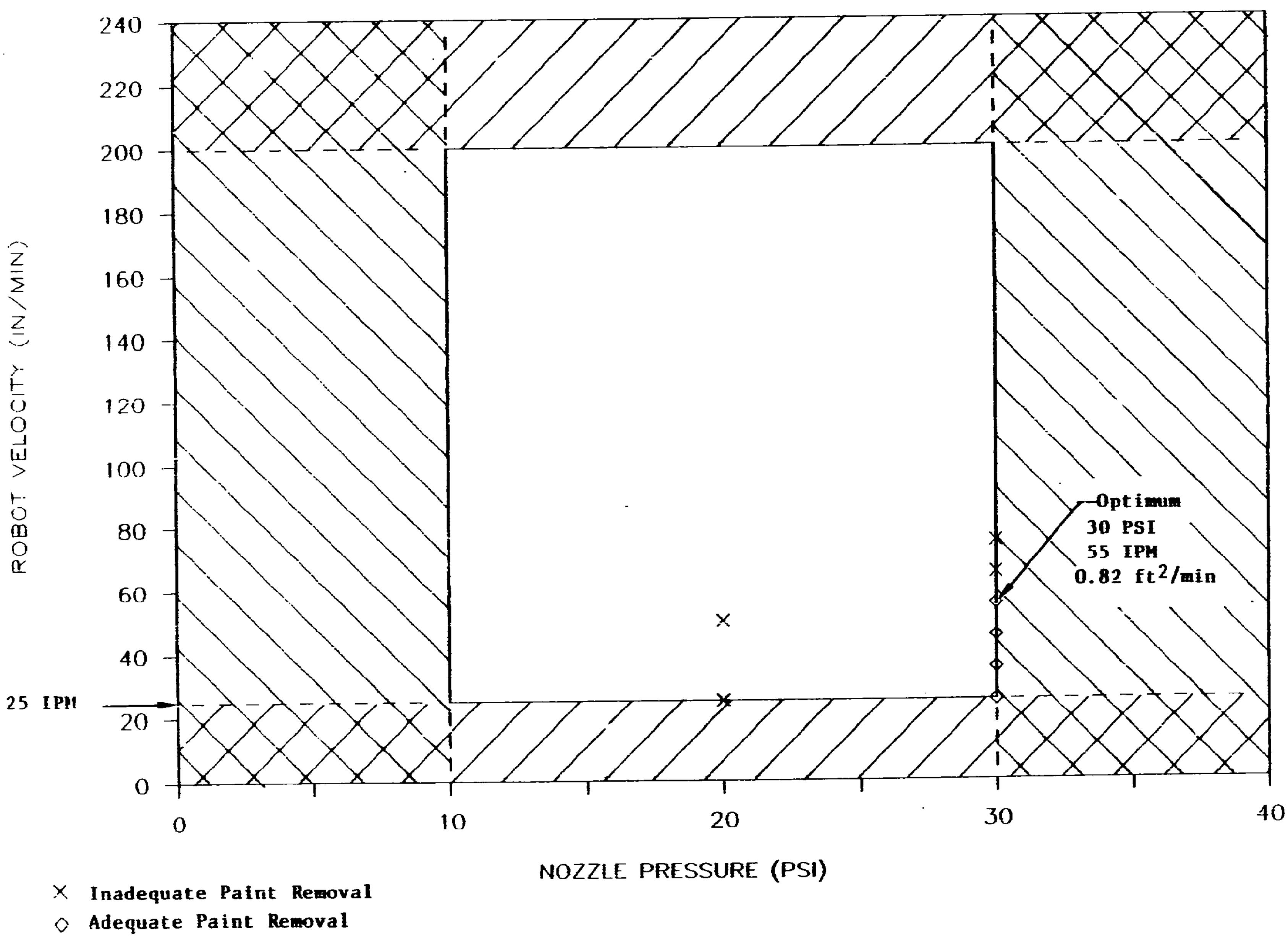
This process of optimization or optimal range-setting is best seen in the robot velocity optimization tests performed in March 1987. It was really a process of finding the appropriate nozzle pressure for each application (see Appendix A, 3/24/87). For example, we tried to strip a difficult F-4 turtleback at 20 PSI. After trying robot velocities of 50 and 25 IPM, it became clear that we would have to increase our pressure to 30 PSI (see Figure 5-13). We were then able to strip the paint adequately at 25 and 55 IPM, but not at 65 or 75 IPM. The optimal settings, therefore, for this difficult turtleback were:

Stand-off - 24"
Mass flow - 7 turns
Robot velocity - 55 IPM
Nozzle pressure - 30 PSI
Paint removal rate - 0.82 ft^2/min.

Throughout the Process Optimization phase, we never had to run up against the limits of nozzle pressure and robot velocity to remove an aircraft coating, including decals and alclad surface. Had it occurred, for example, that we were unable to strip the difficult turtleback even at 30 PSI and 25 IPM, we would have reduced our robot velocity to something less than 25 IPM. Although we have avoided nozzle pressures above 30 PSI in order to minimize the possibility of substrate damage, the standard blast pressure at Hill AFB is 40 PSI, and this pressure remains a possibility to be used when the RPSC is actually built and installed. If higher pressures are used after installation, tests will be performed to maximize robot velocity in order to achieve the highest possible paint removal rate and minimize potential substrate damage.

Figure 5-13

OPTIMIZATION: DIFFICULT F-4 TURTLEBACK



The paint removal rate achieved on the difficult turtleback was a relatively low paint removal rate and represented a class of difficult aircraft surfaces. We were interested in establishing an upper boundary of paint removal rates, so we chose an easy F-4 turtleback and stripped it at maximum nozzle pressure and velocity (see Figure 5-14). For the easy turtleback, therefore, the variables were set at:

Stand-off - 24"
Mass flow - 7 turns
Robot velocity - 200 IPM
Nozzle pressure - 30 PSI
Paint removal rate - 2.92 ft^2/min.

Finally we wanted to know what the optimal paint stripping parameters should be for a graphite composite panel. All three nozzle pressures were tried, and robot velocity was optimized at each one (see Figure 5-15). At 10 PSI the maximum robot velocity was 25 IPM (see photos in Figures 5-16 through 5-18). The paint removal rate was 0.31 ft^2/min. which is very slow and would only be acceptable if it was impossible to strip at higher pressures without damaging the fibers. At 20 PSI, the maximum robot velocity was 75 IPM. This is a very safe and conservative nozzle pressure, where even a momentary dwell did not produce fiber damage. The paint removal rate was 1.29 ft^2/min. which is acceptable for small areas of the aircraft, but is below the target rate for the entire aircraft. At 30 PSI, the maximum robot velocity was 100 IPM, which produced a paint removal rate of 1.59 ft^2/min. This is an excellent rate and is above the target rate of 1.5 ft^2/min. per nozzle (see Appendix B, Parametric Boundaries for Acceptable Paint Removal Rates). Stripping composites at 30 PSI is risky, however, and was described in Section 5.5.

The final conclusions that came out of robot velocity optimization are the following:

1) In programming the RPSC, the appropriate nozzle pressure, mass flow, and stand-off shall be chosen first; then the robot velocity shall be chosen so as to maximize paint removal rate.

2) Robot velocity shall be used as the primary means of responding to a change of conditions and readjusting paint removal effectiveness. In other words, when small difficult areas are encountered (e.g. decals), the robot shall slow down until the coating is removed and then shall resume its previous velocity. Only when the limits of robot velocity have been reached or when moving to entirely new areas shall the nozzle pressure be adjusted.

3) It is the goal of the RPSC not to exceed 30 PSI. If it becomes clear that a particular section of the aircraft cannot be stripped at 30 PSI after all other parameters have been optimized, then either it will be stripped manually or some pressure higher than 30 PSI will be considered.

Figure 5-14

OPTIMIZATION: EASY F-4 TURTLEBACK

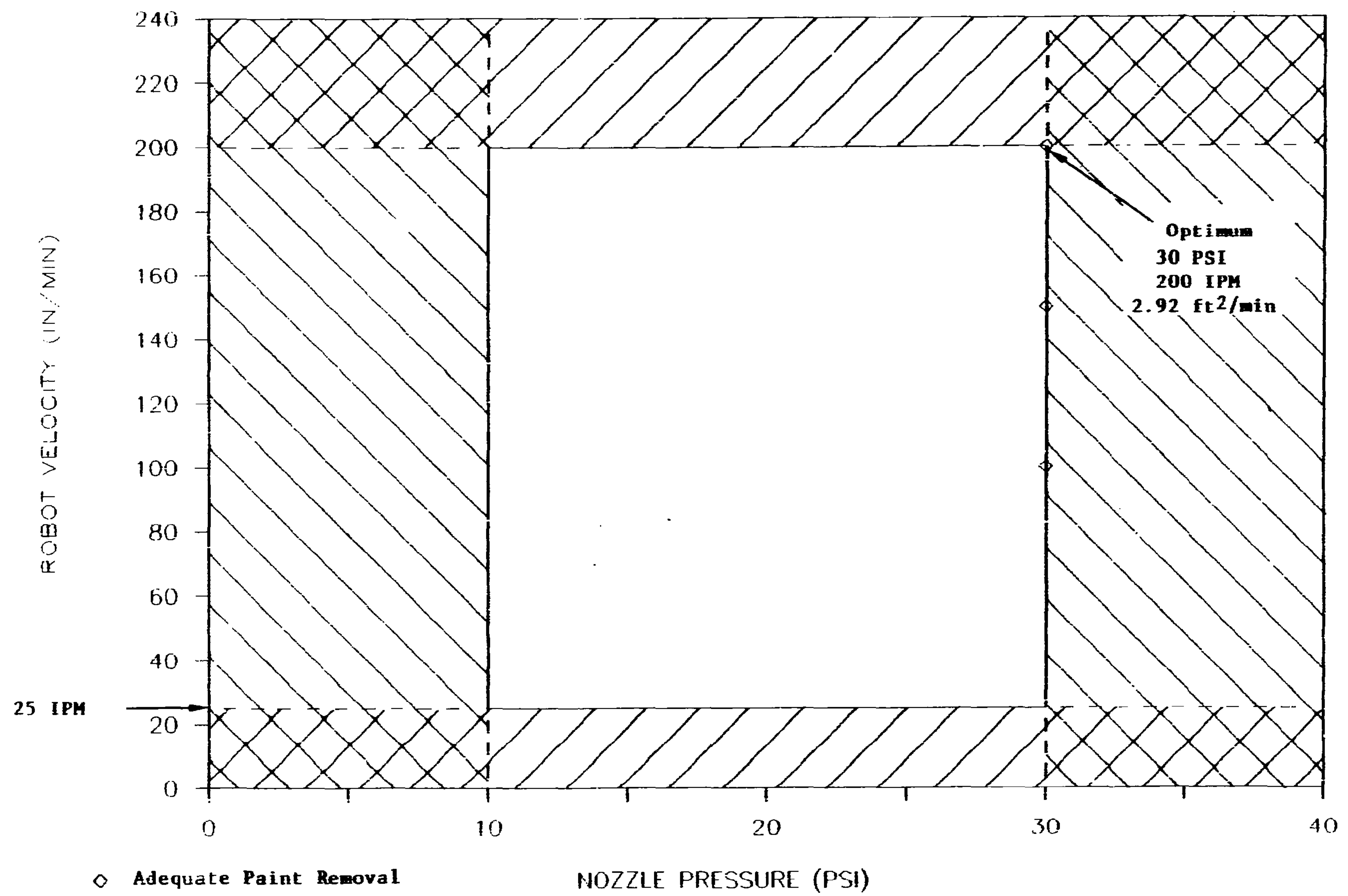


Figure 5-15

OPTIMIZATION: GRAPHITE COMPOSITE PANEL

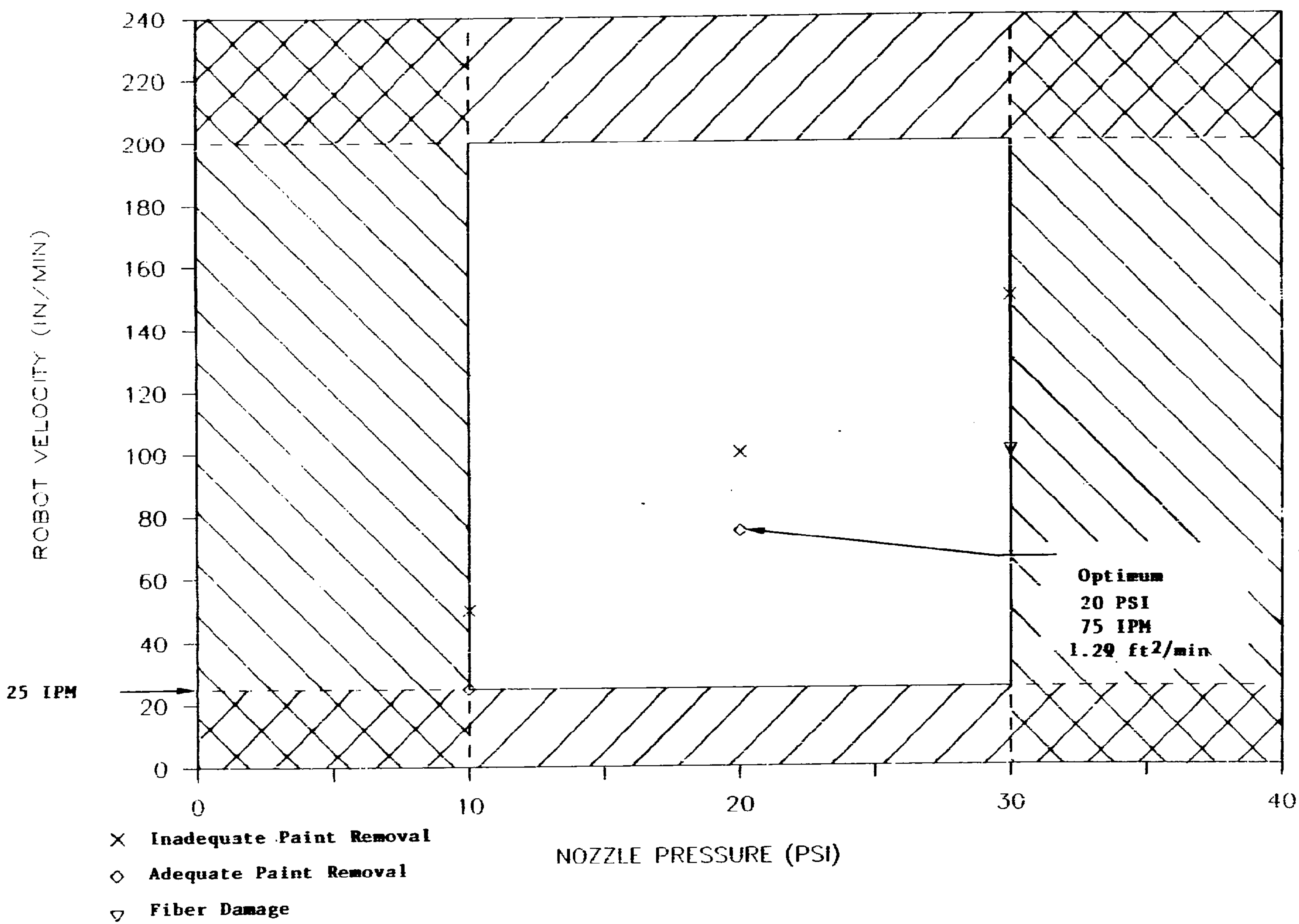
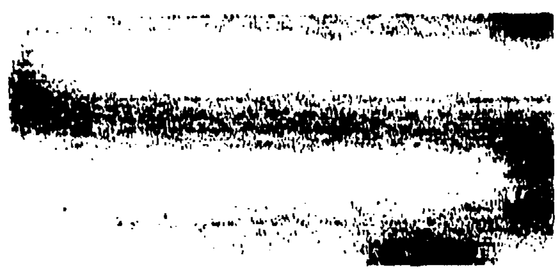


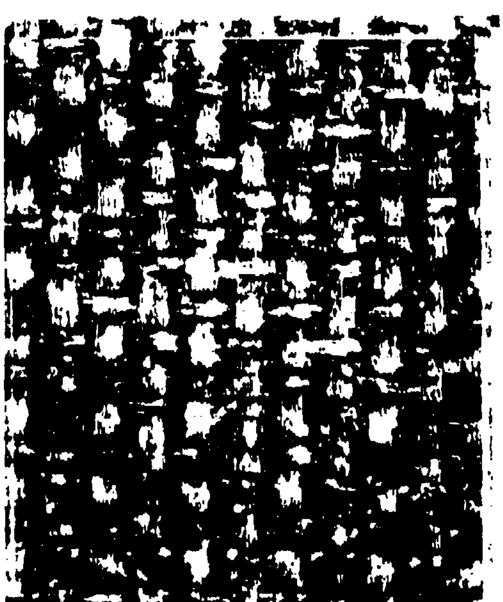
Figure 5-16

OPTIMIZATION OF ROBOT VELOCITY AT 10 PSI NOZZLE PRESSURE

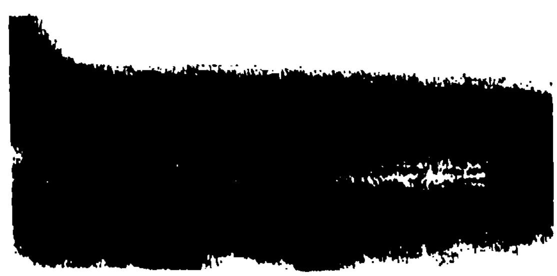
PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-ply
10 PSI, 50 IPM, 442 lbs/hr, MAG: 13X



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
10 PSI, 50 IPM, 442 lbs/hr



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-ply
10 PSI, 25 IPM, 442 lbs/hr, MAG: 13X



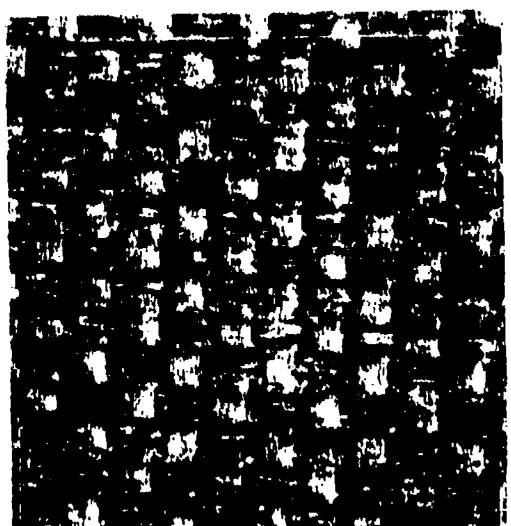
PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
10 PSI, 25 IPM, 442 lbs/hr

Figure 5-17

OPTIMIZATION OF ROBOT VELOCITY AT 20 PSI NOZZLE PRESSURE

PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
20 PSI, 100 IPM, 502 lbs/hr, MAG: 13X

PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
20 PSI, 100 IPM, 502 lbs/hr



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
20 PSI, 75 IPM, 502 lbs/hr, MAG: 13X

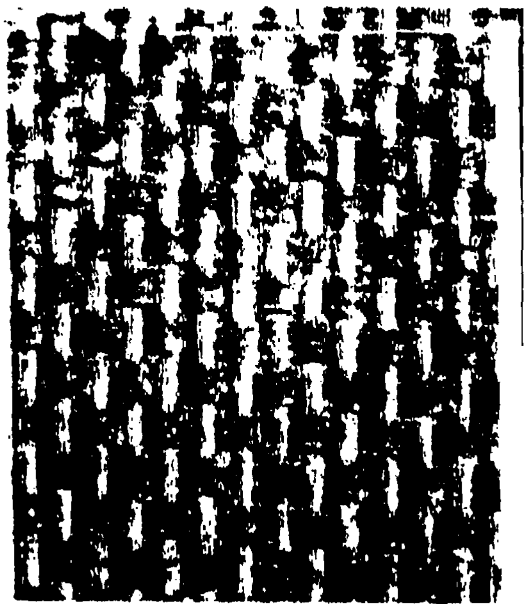
PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
20 PSI, 75 IPM, 502 lbs/hr

Figure 5-18

OPTIMIZATION OF ROBOT VELOCITY AT 30 PSI NOZZLE PRESSURE

PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
30 PSI, 150 IPM, 562 lbs/hr, MAG: 13X

PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
30 PSI, 150 IPM, 562 lbs/hr



PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
30 PSI, 100 IPM, 562 lbs/hr, MAG: 13X

PLASTIC MEDIA PAINT-STRIPPING, 3/26/87
Graphite Composite Panel, 8-Ply
30 PSI, 100 IPM, 562 lbs/hr

5.7 Plastic Media Velocity

The kinetic energy possessed by a solid particle is described by the following equation:

$$KE = 1/2\ MV^2$$

where KE = kinetic energy

M = the mass of the particle

V = the velocity of the particle

The ability of a plastic particle to strip paint is related to its kinetic energy. If it is assumed that the kinetic energy of each particle is totally expended to do work in the form of paint removal, then the rate of work being done by the media is:

$$\frac{dE}{dt} = 1/2 \times \frac{dM}{dt} \times V^2$$

where

$\frac{dE}{dt}$ = the rate of work being done

$\frac{dM}{dt}$ = mass flow rate of plastic media

V = the average velocity of each particle

The rate at which work is done by plastic media blasting is therefore proportioned to mass flow and the square of the velocity of the particle. Theoretically, a change in velocity would produce a much larger relative change in paint removal than a change in mass flow. This is why we became interested in exploring the possibility of controlling the velocity of the media independently of the mass flow rate.

A plastic media blast system (i.e. the typical plastic media blast system), media velocity depends primarily upon nozzle pressure because nozzle pressure brings about higher air velocities, and the compressed air suspends the plastic particles (in dilute phase) and tends to carry them at its own velocity. As each additional plastic particle is added to the airstream, due to the principles of the conservation of momentum, the combined velocity of air and plastic will decrease. Thus not only is media velocity dependent upon nozzle pressure, but it is dependent upon mass flow rate as well. The only possibility we could see of uncoupling mass flow from media velocity, and eliminating nozzle pressure completely, would be to use a centrifugal wheel blaster. We researched it thoroughly and called every manufacturer of centrifugal wheels or turbine blasters. We came to the conclusion that there are still serious design problems to be worked

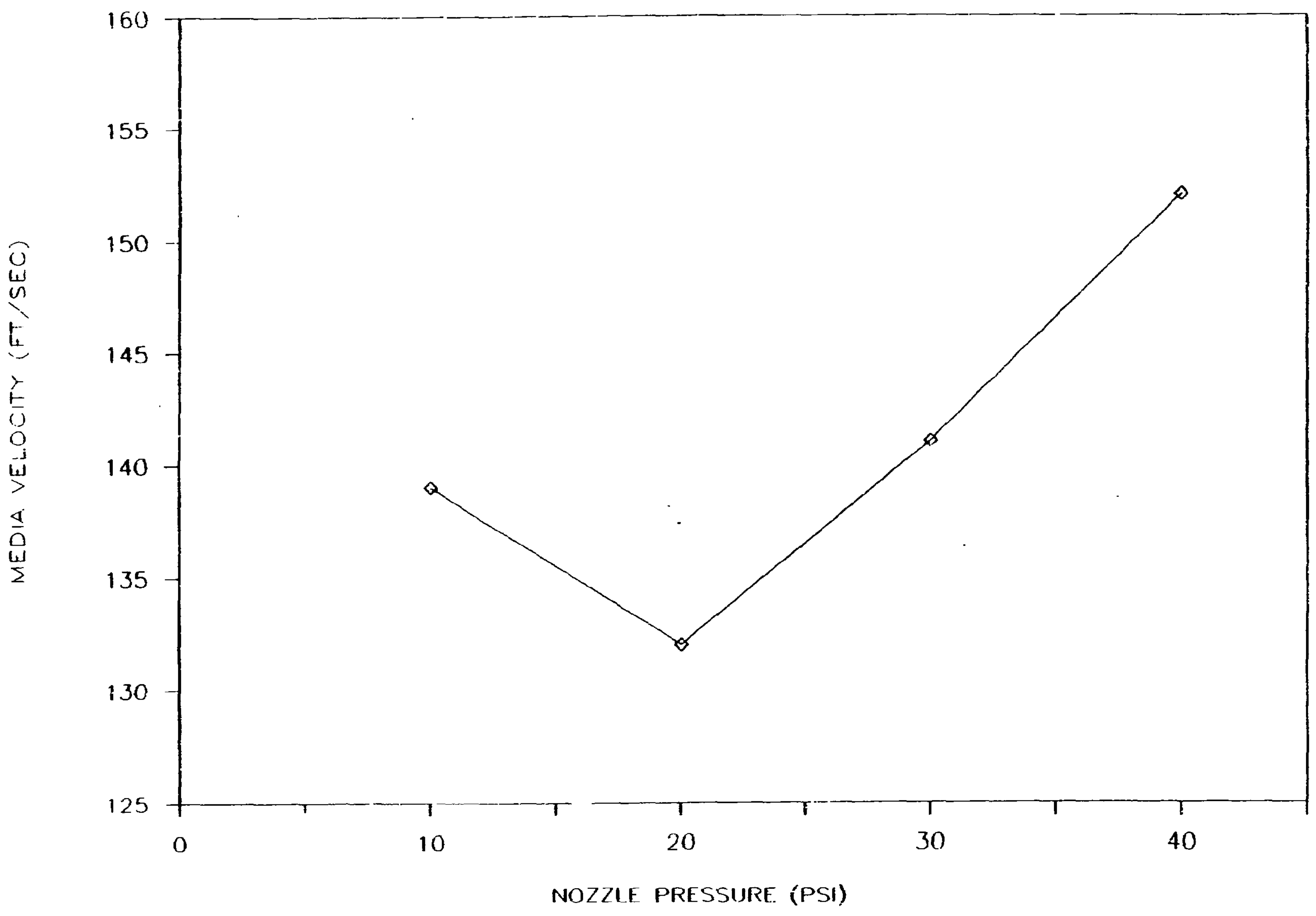
out, and at the present time the portable turbine blaster is not yet available.

On 1/19/87, we attempted to measure plastic bead velocity as a function of nozzle pressure and stand-off distance using a laser doppler velocimeter. Unfortunately, only a weak correlation resulted between bead velocity and nozzle pressure (see Appendix A, 1/19/87). Large velocity errors probably existed because of the fact the equipment was designed for perfectly spherical oil droplets and not irregularly-shaped plastic particles. In looking for trends, however, we noticed that at 24" from the exit of the nozzle, the bead velocity increases with nozzle pressure except at 20 PSI, which produced a lower bead velocity than any other pressure (see Figure 5-19). Although we are cautious about taking this data too seriously, we suspect that while we did not pursue it further, that some special phenomenon is taking place at 20 PSI and 24" stand-off which produces a lower bead velocity. In retrospect, this helps to confirm our choices of 20 PSI and 24" stand-off for use on composites; the lower bead velocity should have a lower risk of doing damage to the substrate.

During the period of time that we were measuring bead velocity, we looked for an instrument that could become part of the RPSC blast hose or end effector that could measure bead velocity. There seemed to be nothing that could withstand the aggressiveness of plastic media. Considering that with an air blast system we cannot change bead velocity without changing nozzle pressure, we discontinued consideration of media velocity measurement and control, and focused instead upon mass flow and nozzle pressure.

Figure 5-19

PLASTIC MEDIA VELOCITY AT 24" STAND--OFF



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APPENDIX A

PROCESS OPTIMIZATION LAB NOTES

Figure A-1

ROBOT VELOCITY TO PAINT REMOVAL RATE CONVERSION CHART

SWATH WIDTH (in.)	ROBOT VELOCITY (IN/MIN)											
	10	20	30	40	50	60	70	80	90	100	150	200
1.0	0.07	0.14	0.21	0.28	0.35	0.42	0.49	0.56	0.63	0.69	1.04	1.39
1.1	0.08	0.15	0.23	0.31	0.38	0.46	0.53	0.61	0.69	0.76	1.15	1.53
1.2	0.08	0.17	0.25	0.33	0.42	0.50	0.58	0.67	0.75	0.83	1.25	1.67
1.3	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72	0.81	0.90	1.35	1.81
1.4	0.10	0.19	0.29	0.39	0.49	0.58	0.68	0.78	0.88	0.97	1.46	1.94
1.5	0.10	0.21	0.31	0.42	0.52	0.63	0.73	0.83	0.94	1.04	1.56	2.08
1.6	0.11	0.22	0.33	0.44	0.56	0.67	0.78	0.89	1.00	1.11	1.67	2.22
1.7	0.12	0.24	0.35	0.47	0.59	0.71	0.83	0.94	1.06	1.18	1.77	2.36
1.8	0.13	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25	1.88	2.50
1.9	0.13	0.26	0.40	0.53	0.66	0.79	0.92	1.06	1.19	1.32	1.98	2.64
2.0	0.14	0.28	0.42	0.56	0.69	0.83	0.97	1.11	1.25	1.39	2.08	2.78
2.5	0.17	0.35	0.52	0.69	0.87	1.04	1.22	1.39	1.56	1.74	2.60	3.47
3.0	0.21	0.42	0.63	0.83	1.04	1.25	1.46	1.67	1.88	2.08	3.13	4.17
3.5	0.24	0.49	0.73	0.97	1.22	1.46	1.70	1.94	2.19	2.43	3.65	4.86
4.0	0.28	0.56	0.83	1.11	1.39	1.67	1.94	2.22	2.50	2.78	4.17	5.56
4.5	0.31	0.63	0.94	1.25	1.56	1.88	2.19	2.50	2.81	3.13	4.69	6.25
5.0	0.35	0.69	1.04	1.39	1.74	2.08	2.43	2.78	3.13	3.47	5.21	6.94

Example: A robot traveling at 100 in/min and creating a stripped swath 1.5" wide is removing paint at the rate of 1.04 ft^2/min.

Date: 12/12/86

Purpose: To try out the Turco Blast 'n Vac System and to optimize pressure, angle, nozzle diameter, stand-off, and travel rate.

Equipment: Turco Blast 'n Vac System with vacuum recovery
185 CFM compressor
DuPont 30/40 sieve size media, 3.5 mohs hardness
Cincinnati Milacron T3-566 hydraulic robot

Procedure: Set mixture control Thompson valve at 50% opening; substrate is alclad aluminum with primer and topcoat; system run in closed vacuum recovery mode.

TABLE A-1. INITIAL TESTS 12/12/87

POT PRESSURE	ANGLE	NOZZLE DIAMETER	STAND-OFF	TRAVEL RATE	SWATH WIDTH	PAINT REMOVAL RATE
20 PSI	90°	.50"	3.25"	25 IPM	2.5"	.43 FT^2/MIN
"	"	"	"	30	2.4"	.50 "
"	"	"	"	35	2.3"	.56 "
"	"	"	"	40	2.2"	.61 "
25 PSI	90°	.50"	3.25"	25 IPM	2.4"	.42 "
"	"	"	"	30	2.3"	.48 "
"	"	"	"	35	2.1"	.51 "
"	"	"	"	40	2.0"	.56 "
20 PSI	70°	.50"	5.5"	25 IPM	2.4"	.42 "
"	"	"	"	30	2.3"	.48 "
"	"	"	"	35	2.2"	.53 "
"	"	"	"	40	2.1"	.58 "
20 PSI	70/70[1]	.50"	5.5"	25 IPM	2.4"	.42 "
"	"	"	"	30	2.3"	.48 "
"	"	"	"	35	2.2"	.53 "
"	"	"	"	40	2.2"	.61 "

Results: Paint was removed to varying degrees

Conclusions: 1) Increasing robot velocity reduces paint removal effectiveness;
2) Changing the angle did not seem to affect paint removal significantly.

[1]Pitch angle - 70°; yaw angle - 70°

Date: 12/12/86

Purpose: To optimize nozzle angle and travel rate

Equipment: Turco Blast 'n Vac System
185 CFM compressor
Cincinnati Milacron T3-566 robot
DuPont 30/40 media, 3.5 mohs hardness
Nozzle diameter: 0.5"

Procedure: Stand-off 5.5" (fixed by vacuum brushes)
Pot Pressure: 20 PSI
Substrate: 8-ply, unidirectional graphite composite with primer and topcoat; blast system run in vacuum recovery mode

TABLE A-2. GRAPHITE COMPOSITE TESTS 12/12/86

ANGLE	TRAVEL RATE	SWATH WIDTH	PAINT REMOVAL RATE
90°	20 IPM	.8"	.11 FT^2/MIN
"	30	.7"	.15 "
"	40	.6"	.16 "
70°	20 IPM	.7"	.10 "
"	30	.6"	.13 "
"	40	.5"	.14 "
70/70	20 IPM	.7"	.10 "
"	30	.6"	.13 "
"	40	.5"	.14 "

Results: Paint and primer completely removed at 20 IPM

Conclusions: Safe paint stripping on composites appears feasible at 20 PSI and 20 in/min.
No apparent difference between 90° and 70°/70° orientation.

Date: 1/19/87

Purpose: To measure plastic bead velocity

Equipment: "Autostripper" blast system from Inventive Machine Corp.
185 CFM compressor
Cincinnati Milacron T3-566 robot
Laser Doppler Velocimeter
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
Nozzle diameter: 1/4"

Procedure: Mixture control valve approximately half open; robot holds the nozzle pointing downward; Laser doppler velocimeter is set up outside the blast booth looking through the plastic curtains

TABLE A-3. PLASTIC BEAD VELOCITIES (FT/SEC)

Stand-off Distance

NOZZLE PRESSURE	POT PRESSURE	0"	3"	6"	12"	18"	23"
10 PSI	17 PSI	137.1	133.8	134.8	144.4	135.7	139.3
20	30	145.7	134.0	131.6	134.0	131.8	131.7
30	38	143.7	146.5	143.1	132.1	147.3	141.0
40	52	159.1	158.6	145.6	129.8	143.4	151.6

Results: Bead velocities did not consistently follow nozzle pressure or stand-off distance

Conclusion: Weak correlation between nozzle pressure and bead velocity. Large velocity errors probably existed because of the fact that the equipment was designed for perfectly spherical oil droplets and not irregularly shaped plastic particles.

Date: 1/20/87

Purpose: To measure plastic media mass flow while varying nozzle pressure

Equipment: Autostripper from Inventive Machine Corp.
U.S. Technology "Polyplus" media, 20/30 sieve size, 3.5 mohs hardness
Nozzle diameter: 1/4"
185 CFM compressor
Plastic barrel and 500 lb. twin-beam scale

Procedure: To blast the plastic media into a plastic barrel for 1 minute at each nozzle pressure while keeping media valve constant at approximately half open

Results: Mass flow rate goes up as nozzle pressure increases

Conclusion: Media mass flow rate is coupled to and increases with blast pressure

TABLE A-4. MASS FLOW RATES WITH AUTOSTRIPPER

NOZZLE PRESSURE	SYSTEM PRESSURE	TIME INTERVAL	WEIGHT OF MEDIA	MASS FLOW RATE (LBS/HR)
5	13	1 MIN.	5 LBS	300
10	18	"	6	360
15	25	"	7	420
20	30	"	7	420
25	35	"	7	420
29	41	"	8	480
35	53	"	8.5	510
40	48	"	9.25	555

Date: 1/22/87

Purpose: To try out various nozzle shapes

Equipment: Autostripper Blast System
Polyplus 20/30 media, 3.5 mohs hardness
185 CFM compressor
Cincinnati Milacron T3-566 robot

Manual Paint Stripping:

Procedures

1. 18 PSI nozzle pressure, 1/2" round copper tube nozzle, one ft^2 anodized aluminum panel, 19.21 secs.

   Paint Removal Rate: 3.1 ft^2/min.

2. 18 PSI nozzle pressure, 3/4" x 5/16" oval copper tube nozzle, one ft^2 anodized aluminum panel, 22.93 secs.

   Paint Removal Rate: 2.6 ft^2/min.

Robotic Paint Stripping

Procedure: 12" stand-off, 90° nozzle angle.
See Table A-5.

TABLE A-5. NOZZLE SHAPE OPTIMIZATION TESTS

FIXED CONDITIONS: STAND-OFF 12", NOZZLE ANGLE 90°

NOZZLE SHAPE	NOZZLE PRESSURE	ROBOT VELOCITY	SWATH WIDTH	PAINT REMOVAL RATE	COMMENTS
1/8x3/4" Oval	18 PSI	40 in/min	3-1/4"	0.9 ft^2/min	Anodized Panel; Removed paint completely
"	"	100 in/min	2-3/4"	1.9 ft^2/min	Removed paint completely, Same Panel
"	"	150 in/min	2-1/4"	2.3 ft^2/min	Removed paint completely, slowed to 30 in/min over decal; Same Panel
"	30 PSI	100 in/min	2-1/4"	1.6 ft^2/min	Alclad Panel; Removed paint, left some primer
Dog bone	"	120 in/min	1" to 2-1/2"	1.7 ft^2/min	Same panel; Larger side of nozzle strips better; very little primer removed
3/16x7/8" Oval	20 PSI	100 in/min	2-1/2 to 3"	2.1 ft^2/min	T-38 anodized panel; Paint removed completely
"	"	"	3-1/2"	2.4 ft^2/min	F-4 panel with alodyne, primer and paint; removed paint/primer completely
"	"	200 in/min	2-1/2"	3.5 ft^2/min	Same panel; removed paint entirely; left some primer

Results: Paint removal rates varied from 0.9 ft^2/min. to 3.5 ft^2/min. Paint was removed from alclad, anodized, and alodyned surfaces using the oval nozzle.

Conclusions:

1) Paint removal rate is more dependent upon robot velocity than swath width.
Corollary: Although increasing robot velocity will decrease swath width, the net effect is an increase in paint removal rate.

2) Paint removal rate depends most heavily on the type of substrate and nature of the coatings.

3) To increase robot velocity is a convenient and effective means of varying the paint removal rate on a constant substrate; changing nozzle pressure is an effective but not a convenient way of changing paint removal rate on a constant substrate.

4) Changing the robot velocity is not an effective way to handle more difficult substrates; increasing nozzle pressure is an effective way to handle more difficult substrates while maintaining reasonable paint removal rates.

5) The most convenient means of stripping decals is to lower robot velocity momentarily while traveling over decal region.

6) The effect of nozzle shape was insignificant in comparison with the type of substrate, the nozzle pressure, and the robot velocity.

7) The blast pattern is almost unaffected by nozzle shape; the center is still well-stripped and the edges are "fuzzy". It would probably be better to place two nozzles side-by-side allow their blast patterns to overlap.

Date: 1/26/87

Purpose: To measure mass flow rate as a function of nozzle pressure.

Equipment: Autostripper Blast System
185 CFM compressor
Plastic barrel to catch plastic media
500 lb. twin-beam scale to measure nozzle output
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness

Results: Plastic media collected increased from 10 lbs in one minute at 4 PSI nozzle pressure to 16 lbs in one minute at 10 PSI nozzle pressure.

Conclusions: This data is suspect because a significant amount of media escaped from the barrel during blasting.

TABLE A-6

NOZZLE PRESSURE	STATIC SYSTEM PRESSURE	TIME INTERVAL	WT. OF MEDIA	MASS FLOW RATE (LBS/HR)
4 PSI	35 PSI	1 MIN	10 LBS	600
6 PSI	40 PSI	"	14 LBS	840
10 PSI	60 PSI[1]	"	16 LBS	960

[1]The gauge on the Autostripper does not go higher than 60 PSI; also the compressor had difficulty reaching this pressure.

Date: 1/27/87

Purpose: To investigate the effect of a Y-shaped dual nozzle.

Equipment: Autostripper Blast System
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
Cincinnati Milacron T3-566 robot
Y-shaped nozzle made of 1/2" copper tube and 2-3/4" spacing between nozzle centers.

Procedure:

TABLE A-7. OPTIMIZATION TESTS WITH Y-SHAPED NOZZLE

Fixed Conditions: Anodized T-38 Panel

NOZZLE PRESSURE	ROBOT VELOCITY	STAND-OFF	SWATH WIDTHS	PAINT REMOVAL RATE	COMMENTS
18 PSI	50 IPM	12"	2" AND 2"	1.4 FT^2/MIN	LEFT 1" UNSTRIPPED REGION BETWEEN SWATHS
"	"	15"	2-1/2" AND 1-1/2"	"	LEFT 1" UNSTRIPPED REGION
"	"	9"	1" AND 1"	0.7 FT^2/MIN	LEFT 1-1/2" UNSTRIPPED REGION. DID NOT STRIP ON ALCLAD REGION
"	"	15"	1-1/2" AND 1"	0.5 FT^2/MIN	LEFT 1" UNSTRIPPED REGION
23 PSI	"	12"	ONE SOLID 5" SWATH	1.7 FT^2/MIN	NOZZLE PINCHED DOWN TO 1/4" X 3/4"; ANODIZED REGION
"	"	12"	2" AND 1"	0.8 FT^2/MIN	SAME NOZZLES; ALCLAD REGION
12 PSI	"	12"	NONE	--	FLIP-SIDE OF ANODIZED PANEL[1]
"	"	9"	1-1/3" AND 1-1/3"	1.0 FT^2/MIN	LEFT 1" UNSTRIPPED REGION; SAME PANEL

[1]Paint does not appear to adhere better but is probably much thicker.

Results:

1) Paint was stripped to varying degrees at 12 PSI, 18 PSI, and 23 PSI, and at stand-off distances of 9", 12", and 15".

2) In most tests, two separate swaths were obtained with an unstripped region in between.

3) Swath widths varied from nothing to 2-1/2". At 23 PSI and 12" stand-off, on anodized substrate, a solid 5" swath was achieved.

4) Paint removal rate varied from zero on an alclad region to 1.7 ft^2/min on an anodized region.

5) At 18 PSI, on an anodized panel the maximum swath width and, therefore, the maximum paint removal rate occurred at 12" stand-off.

6) Under identical conditions, the paint removal rate for an anodized region was 1.7 ft^2/min and for an alclad region was 0.8 ft^2/min.

7) At 12 PSI on an anodized panel with thick paint, the paint removal rate was 1.0 ft^2/min at a 9" stand-off and zero at a 12" stand-off.

Conclusions:

1) For a given nozzle pressure, robot velocity, substrate, and coating, there is an optimal stand-off distance which will give the highest paint removal rate. A shorter stand-off will produce a narrower swath and therefore, a lower paint removal rate. Longer stand-off will produce a narrower swath or no swath at all, and once again a lower removal rate.

2) As a rule-of-thumb, anodized aluminum is stripped approximately twice as fast as alclad.

   Corollary 1) At roughly half the nozzle pressure, anodize will strip just as quickly as alclad.

   Corollary 2) At roughly twice the stand-off distance, anodize will strip just as quickly as alclad.

   Corollary 3) At roughly twice the robot velocity, anodize will strip just as quickly as alclad.

3) Optimal stand-off distance is heavily dependent upon nozzle pressure and substrate.

4) When two nozzles leave an unstripped region between two stripped swaths, one or more of the following changes must be made:

- nozzle pressure must be increased
- robot velocity must be lowered
- stand-off distances must be moved toward the optimum (this could require that it is raised or lowered depending upon the other conditions).
- The center-to-center distance of the two nozzles must be reduced.

Date: 2/2/87

Purpose: To test proximity sensor for sensitivity to plastic bead interference.

Equipment: Autostripper Blast System
250 CFM compressor
Cincinnati Milacron T3-566 robot
Amerace Corporation "Agastat" Ultrasonic Proximity Sensor

TABLE A-8. PROXIMITY SENSOR INTERFERENCE TEST

NOZZLE STAND-OFF	SENSOR STAND-OFF	STATIC READING	READING WITH AIR/MEDIA FLOW
12"	16.5"	22.12 mA	19.27 - 22.11 mA
9"	13.5"	20.95 mA	18.75 - 20.95 mA
6"	10.5"	17.04 mA	15.40 - 17.04 mA

Results: Sensor readings fluctuated below static reading during blasting. Sensor readings increased with sensor stand-off for both static and blasting conditions.

Conclusions: The flow of air and plastic beads causes the sensor reading to fluctuate rapidly, but the maximum reading is equal to the static condition for that stand-off.

Date: 2/2/87

Purpose: To investigate paint removal rate of Y-shaped nozzle on various substrates.

Equipment: Autostripper Blast System
Cincinnati Milacron T3-566 Robot
250 CFM compressor
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
Y-shaped nozzle made of 1/2" copper tube and 2-3/4" spacing between nozzle centers.

Results:

TABLE A-9. PAINT STRIPPING WITH Y-SHAPED NOZZLE

Fixed Conditions: Nozzle Pressure - 30 PSI
Stand-off - 12"

SUBSTRATE	NOZZLE PRESSURE	ROBOT VELOCITY	STAND-OFF	PAINT REMOVAL RATE	COMMENTS
T-38 ALCLAD HONEYCOMB	30 PSI	50 IPM	12"	1.00 FT^2/MIN	DID NOT STRIP COMPLETELY
T-38 ANODIZED ALUMINUM	"	"	"	1.33 FT^2/MIN	STRIPPED ENTIRELY, PERHAPS OVERKILL
GRAPHITE PANEL	"	"	"	0.66 FT^2/MIN	LEFT 2" UNSTRIPPED PATH BETWEEN SWATHS
GRAPHITE PANEL	"	35 IPM	"	0.99 FT^2/MIN	LEFT 1" UNSTRIPPED PATH BETWEEN SWATHS

Conclusions:

1) A y-shaped dual nozzle strips anodized aluminum faster than alclad aluminum.

2) A y-shaped dual nozzle strips aluminum faster than graphite composite.

3) A 2-3/4" spacing between nozzles is too wide to achieve a solid swath with this dual nozzle at 30 PSI on graphite composite.

4) These tests are not truly representative of a 30 PSI test since two nozzles are sharing the same blast hose and there is no constricted/expended region to accelerate the media.

Date: 2/12/87

Purpose: To demonstrate robotic plastic media paint stripping for USAF/MAWF personnel.

Equipment: Autostripper Blast System
Cincinnati Milacron T3-566 Robot
250 CFM compressor
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
1/2" copper tube nozzle
T-38 anodized wing section
90° nozzle orientation

TABLE A-10. PAINT STRIPPING DEMO FOR MAWF PERSONNEL

Fixed Conditions: **90° nozzle orientation, 12" stand-off, 25 PSI nozzle pressure, 1/2" copper tube nozzle with pinched exit. T38 test panel with anodize, primer, and polyurethane paint**

ROBOT VELOCITY	SWATH WIDTH	PAINT REMOVAL RATE	COMMENTS
35 IPM	3-1/2"	.85 FT^2/MIN	REMOVED PAINT & PRIMER
20 IPM	---	----	DID NOT REMOVE DECAL
35 IPM	3-1/2"	.85 FT^2/MIN	REMOVED PAINT & PRIMER
10 IPM	---	----	REMOVED DECAL WELL, DID NOT REMOVE PAINT

Results: Paint was removed at higher velocity; decal was removed by lowering robot velocity.

Conclusions: Robot velocity must be substantially lower to remove decal, but it can be done without having to change nozzle pressure or stand-off.

Date: 3/13/87

Purpose: To try out the Schmidt PMB-BV Blast System; to optimize paint removal rate as a function of robot velocity.

Equipment: Schmidt PMB-BV Blast System
250 CFM compressor
Cincinnati Milacron T3-566 robot
Schmidt 1/2" blast nozzle
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness

Procedure:

TABLE A-11. SCHMIDT PMB-BV BLAST SYSTEM TRY-OUT

Fixed Conditions: **F-4 leading edge test panel**
24" stand-off
30 PSI pot pressure
90° nozzle angle
Thompson (media) valve setting: 5 turns (50% open)

ROBOT VELOCITY	SWATH WIDTH	PAINT REMOVAL RATE	COMMENTS
50 IPM	3"	1.04 FT^2/MIN	GRAY SIDE OF PANEL
120 IPM	1-1/2"	1.25 FT^2/MIN	SAME SIDE
60 IPM	2-3/4"	1.15 FT^2/MIN	SAME SIDE
60 IPM	1-3/4"	0.73 FT^2/MIN	FLIP SIDE OF SAME PANEL (WHITE SIDE)
60 IPM	4-1/2"	0.94 FT^2/MIN	TWO PASSES OVER THE SAME PATH

Results:
1) Paint came off more quickly on the gray side than on the white side.
2) Higher robot velocities decreased swath width but increased overall paint removal rate.
3) Two passes over the same path gave a higher net removal rate than one pass.

Conclusions:
1) The substrate and/or the paint was different on the white side than on the gray side.
2) Although it decreases swath width, increasing the robot velocity is an effective and convenient means of increasing paint removal rate.
3) Overlapping swaths will give higher paint removal rates than lying swaths side-by-side.

Date: 3/16/87

Purpose: To measure mass flow rate as a function of blast pressure and media valve opening.

Equipment: Schmidt PMB-BV System
250 CFM compressor
1/2" blast nozzle
U.S. Technology Polyplus 20/30 media, 3.5 mohs hardness
250-lb. cardboard drum
Dual beam scale

Procedure: A plastic covering was taped over the top of the cardboard drum and the blast nozzle was held through a slit in the covering while plastic media was blasted into the drum. Media was blasted for one minute at each valve opening and each of three pressures.

Fixed Conditions: Blast nozzle held downward by hand, blasting directly into the cardboard drum.

Results:

TABLE A-12. SCHMIDT PMB-BV BLAST SYSTEM MASS FLOW MEASUREMENTS: RAW DATA (LBS/MIN.) RECORDED ON 3/16/87

NOZZLE PRESSURE (PSI)	MEDIA CONTROL VALVE POSITION (TURNS) 1	2	3	4	5	6	7	8	9	10
10	0	0	0	1.25	2.25	4.25	4.50	5.5	6	5.25
				1.25	2.50	3.50	4.75	5.5	5.75	5.50
Average				1.25	2.375	3.875	4.625	5.5	5.875	5.375
20	0	0	0	.75	1.5	2.25	4.5	5.0	4.5	3.5
				.75	1.75	2.75	4.25	4.5	4.5	--
Average				.75	1.625	2.50	4.375	4.75	4.5	3.5
26	.25	.25	0	2.5	3.5	5	4.5	4.75	4.75	3.5
	.25	0	--	2.5	3.75	4.25	--	--	--	--
Average	.25	.125	0	2.5	3.625	4.625	4.5	4.75	4.75	3.5

Comments:

1) At 10 turns much media was lost through the slit in the plastic covering.

2) The air compressor could not reach 30 PSI. The pressure actually varied between 25-27 PSI.

3) At 26 PSI and above 4 turns, the compressor could not keep up with the demand.

4) At 26 PSI and above 6 turns, much media was lost through the openings in the cardboard drum.

TABLE A-13. CONVERTED MASS FLOW MEASUREMENTS (LBS/HR) FROM DATA RECORDED ON 3/16/87

NOZZLE PRESSURE (PSI)	MEDIA CONTROL VALVE POSITION (TURNS) 1	2	3	4	5	6	7	8	9	10
10	0	0	0	75	14.25	232.5	277.5	330	352.5	322.5
20	0	0	0	45	9.75	150	262.5	285	270	210
30	15	7.5	0	150	217.5	277.5	270	285	285	210

Conclusions:

1) Mass flow rate increases with the opening of the valve until you get to about 8 or 9 turns; then it begins to drop off about 10-20% until it is fully open at 10 turns.

2) For the three nozzle pressures tested, mass flow rate is lowest at 30 PSI and highest at 10 PSI. This ranking is independent of the valve opening.

3) At 20 and 30 PSI, the flow of the air/media mixture is loud, dusty, and violent, exerting large sporadic forces against the sides of the container. This indicates a typical flow of pressurized, airborne media.

4) At 10 PSI, the flow of the air and media is soft, subdued, not so dusty, not so loud, and exerts a small but consistent force against the sides of the container. This indicates the typical dense phase flow of solid media being "pushed" by compressed air.

5) The trends of this data seem reliable, but the numerical values are suspect because of the large amount of media which escaped through the openings in the container.

Date: 3/18/87

Purpose: To measure mass flow rate as a function of blast pressure and media valve opening.

Equipment: Schmidt PMB-BV Blast System
250 CFM compressor
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
U.S. Technology Polyplus 20/30 media, 3.5 mohs hardness
55-gallon steel drum with steel mesh filter and exhaust vent
Dual beam scale

Procedure: Plastic media was blasted into the 55-gallon drum for one minute at 3 pressures and 10 valve settings. This mass flow was extrapolated to lbs/hr.

Fixed Conditions: Blast nozzle held downward by robot, blasting directly into 55-gallon drum.

Results:

TABLE A-14. SCHMIDT PMB-BV BLAST SYSTEM MASS FLOW MEASUREMENTS: Raw Data (lbs/min) Recorded on 3/18/87

Nozzle Pressure (PSI)	Media Control Valve Position (turns) 1	2	3	4	5	6	7	8	9	10
10	0	0	0	2.75	5.5	7.5	11.25	10.5	13.5	12.75
				2.75	5.25	7.25	10.25	10.75	13.25	13.25
AVG:	0	0	0	2.75	5.375	7.375	10.75	10.625	13.375	13
20	0	0	0	1.75	4.25	6.25	8.5	10.5	10.25	11.75
				0.75	4.25	6.5	8.25	9.25	10.75	11
AVG:	0	0	0	1.25	4.25	6.375	8.375	9.875	10.5	11.375
30	0	0	0	1.75	4	6.25	8.75	9.25	9.5	11.75
						6.25	10	9.25	9.5	11
AVG:	0	0	0	1.75	4	6.25	9.375	9.25	9.5	11.375

TABLE A-15. SCHMIDT PMB-BV BLAST SYSTEM AVERAGE MASS FLOW RATES

Converted Data Units: Pounds/hour

Nozzle Pressure (PSI)	Control Valve Position (turns) 1	2	3	4	5	6	7	8	9	10
10	0	0	0	165	322.5	442.5	645	637.5	802.5	780
20	0	0	0	75	255	382.5	502.5	592.5	630	682.5
30	0	0	0	105	240	375	562.5	555	570	682.5

Conclusions:

1) Mass flow rate increases with valve opening.

2) 20 PSI nozzle pressure tends to have a lower mass flow rate at all openings than either 10 PSI or 30 PSI.

3) 10 PSI nozzle pressure tends to have a higher mass flow rate than 30 PSI. The reason is suspected to be that at 10 PSI, the media is traveling in dense rather than dilute phase.

4) At 1, 2, and 3 turns the media valve is not yet open, or is open so little that no noticeable amount of media escapes.

Date: 3/19/87

Purpose: To investigate the effect of plastic media mass flow upon paint removal rate.

Equipment: Schmidt PMB-BV Blast System
250 CFM Compressor
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
U.S. Technology Polyplus 20/30 media, 3.5 mohs hardness.
Test Panel: F-4 turtleback

Procedure: Four swaths are stripped on an F-4 turtleback at a 12" stand-off. Robot velocity and nozzle pressure are constant in each swath. Four valve positions are tested within each swath.

Results:

TABLE A-16. PLASTIC MEDIA MASS FLOW OPTIMIZATION RAW DATA

Fixed Condition: 12" stand-off

NOZZLE PRESSURE	ROBOT VELOCITY	VALVE POSITION	SWATH WIDTH	PAINT REMOVAL RATE	COMMENTS
10 PSI	100 IPM	5 TURNS	0	0	LEFT MUCH PRIMER
		6	0	0	"
		7	0	0	"
		8	0	0	"
20 PSI	50 IPM	5 TURNS	1.5"	0.52 FT^2/MIN	COMPLETELY STRIPPED
		6	1.75"	0.61 "	"
		7	1.85"	0.64 "	"
		8	1.75"	0.61 "	"
	100 IPM	5 TURNS	1.35"	.93 "	LEFT SOME PRIMER
		6	1.35"	.93 "	COMPLETELY STRIPPED
		7	1.5	1.04 "	"
		8	1.4	0.97 "	"
	200 IPM	5 TURNS	0	0	LEFT MUCH PRIMER
		6	0	0	"
		7	0	0	"
		8	0	0	"
30 PSI	50 IPM	5 TURNS	1.7	0.59 "	COMPLETELY STRIPPED
		6	1.9	0.66 "	"
		7	2.0	0.69 "	"
		8	2.0	.93 "	"
	100 IPM	5 TURNS	1.35	.93 "	"
		6	1.35	.93 "	"
		7	1.40	.97 "	"
		8	1.40	.97 "	"

Conclusions:

1) As usual, nozzle pressure has the strongest effect upon paint removal rate. Robot velocity and valve position have approximately a secondary equal effect.

2) Paint is stripped faster at 7 turns of the media valve than at any other valve position.

3) A nozzle pressure of 10 PSI at 100 IPM is sufficient to remove paint but not paint and primer.

Date: 3/20/87

Purpose: To optimize nozzle stand-off at 20 PSI and 50 IPM.

Equipment: Schmidt PMB-BV Blast System
250 CFM compressor
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
U.S. Technology Polyplus 20/30 media, 3.5 mohs hardness
Test Panel: F-4 turtleback

Procedure: One swath of an F-4 turtleback is stripped at an increasing stand-off from 12" to 24".

Results:

TABLE A-17. NOZZLE STAND-OFF OPTIMIZATION AT 20 PSI AND 50 IPM

Fixed Conditions: **Nozzle Pressure - 20 PSI**
Robot Velocity - 50 IPM
Media Valve Opening - 7 turns

NOZZLE STAND-OFF	SWATH WIDTH	PAINT REMOVAL RATE	COMMENTS
12"	1.65"	0.57 FT^2/MIN	COMPLETELY STRIPPED
15"	1.75"	0.61 FT^2/MIN	"
18"	1.85"	0.64 FT^2/MIN	"
21"	1.90"	0.66 FT^2/MIN	"
24"	1.90"	0.66 FT^2/MIN	"

Conclusions:

1) At 20 PSI and 50 IPM, the paint removal rate continuously increases as stand-off goes from 12" to 24".

2) The increase in paint removal rate diminishes as stand-off approaches 24". The optimal stand-off at 20 PSI and 50 IPM is 24" or slightly higher.

3) At 20 PSI and 50 IPM, it does not hurt paint removal rate much to fluctuate between 24" and 15" stand-off.

Date: 3/23/87

Purpose: To determine whether the paint removal effects of plastic media blasting are additive; specifically, to determine whether one pass at 50 IPM is the same as two passes at 100 IPM.

Equipment: Schmidt PMB-BV Blast System
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
250 CFM compressor
Test panel: F-4 turtleback

Procedure: A 12" x 12" square area is laid out on the F-4 turtleback. The paint is removed as the robot travels back and forth over this area in 5 passes, with a spacing of 2-1/2 inches between successive passes (see Figure A-1). Robot velocity is set at 50 IPM or 100 IPM.

TABLE A-18. ADDITIVE PAINT REMOVAL EFFECTS OF PLASTIC MEDIA BLASTING

Fixed Conditions:
Stand-off 24"
Nozzle pressure - 20 PSI
Media valve opening - 7 turns
Spacing between passes - 2-1/2"
Number of passes in robot program - 5

ROBOT VELOCITY	NET EFFECTIVE PAINT REMOVAL RATE	COMMENTS
100 IPM	----	LEFT MUCH PRIMER
"	0.72 FT^2/MIN	SECOND STRIP CYCLE OVER THE SAME PANEL; PAINT & PRIMER COMPLETELY REMOVED EXCEPT FOR 1/2" UN-STRIPPED REGIONS BETWEEN SWATHS
50 IPM	0.72 FT^2/MIN	PAINT AND PRIMER COMPLETELY RE-MOVED EXCEPT FOR 1/2" REGIONS BETWEEN SWATHS

Conclusions: Paint removal effects of plastic media blasting are additive; specifically, one strip cycle at 50 IPM is the same as two cycles over the same equal panel at 100 IPM.

Date: 3/23/87

Purpose: To optimize nozzle stand-off at 20 PSI and 100 IPM.

Equipment: Schmidt PMB-BV blast system
250 CFM compressor
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
U.S. Technology Polyplus 20/30 media, 3.5 hardness
Test Panel: F-4 turtleback

Procedure: One swath of a F-4 turtleback is stripped at an increasing stand-off from 12" to 36".

Results:

TABLE A-19. NOZZLE STAND-OFF OPTIMIZATION AT 20 PSI AND 100 IPM

Fixed Conditions: **Nozzle Pressure - 20 PSI**
Robot Velocity - 100 IPM
Media Valve Opening - 7 turns

NOZZLE STAND-OFF	SWATH WIDTH	PAINT REMOVAL RATE	COMMENTS
10"	1.6"	1.11 FT^2/MIN	COMPLETELY STRIPPED
15"	1.5"	1.04 FT^2/MIN	"
18"	1.5"	"	"
21"	1.4"	.97 FT^2/MIN	"
24"	1.3"	.90 FT^2/MIN	LEFT SOME PRIMER
27"	1.2"	0.83 FT^2/MIN	"
30"	1.0"	0.69 FT^2/MIN	LEFT MUCH PRIMER
33"	0	0	"
36"	0	0	"

Conclusions:

1) At 20 PSI and 100 IPM, the paint removal rate continually decreases as stand-off goes from 12" to 36".

2) The decrease in paint removal rate is about 10% from 12" to 21".

3) At 20 PSI an 100 IPM, the paint removal rate falls off rapidly beyond 2.7".

4) At 20 PSI and 100 IPM, there is a threshold between 30" and 53" stand-off beyond which the media cannot break through the primer and no swath is created. Although this appears to be a discrete jump in paint removal effectiveness, breakdown of the primer's adhesive bond is a continuous function, and at 33" stand-off that bond is almost destroyed.

5) Abrasion of the coating surface is also a continuous function, and at 33" stand-off much coating has been removed.

6) The mechanism of coatings removed, at least for this F-4 panel, is partially an impact effect which destroys the adhesive bond and partially an abrasive effect which wears the coating away starting at the surface.

7) The mechanism of paint removal depends largely upon the substrate and the coatings. If the prevailing mechanism is the impact effect, then a great deal can be gained by going slightly over the adhesive bond threshold. This can be done by any means which increases aggressiveness (e.g. nozzle pressure, stand-off, etc.). If the prevailing mechanism is abrasion, then, then a little gain in aggressiveness will yield only a little gain in paint removal effectiveness.

Date: 3/24/87

Purpose:
1) To eliminate the unstripped region by reducing the spacing between passes.
2) To maximize paint removal rate on a difficult F-4 turtleback test panel.
3) To determine how best to remove difficult coating or deal with difficult substrate.

Equipment:
Schmidt PMB-BV Blast System
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
250 CFM compressor
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
Test panel: F-4 turtleback

Procedure: An approximate 12" x 12" area is laid out on the F-4 turtleback. The paint is removed as the robot travels back and forth over this area in 6 passes with a spacing of 2-1/4" between successive passes. The actual stripped area is later measured. Robot velocity is readjusted according to the observed results.

Results:

TABLE A-20. PAINT REMOVAL OPTIMIZATION ON A DIFFICULT F-4 TURTLEBACK

Fixed Conditions:
Stand-off - 24"
Media valve opening - 7 turns
Spacing between passes - 2-1/4"
Number of passes in robot program - 6

NOZZLE PRESSURE	ROBOT VELOCITY	PAINT REMOVAL RATE	COMMENTS
20 PSI	50 IPM	-----	DID NOT REMOVE PAINT
"	25 IPM	-----	DID NOT REMOVE ALL PAINT
30 PSI	"	0.44 FT^2/MIN	REMOVED PAINT/PRIMER COMPLETELY
"	55 IPM	0.82 FT^2/MIN	REMOVED PAINT/PRIMER COMPLETELY
"	75 IPM	-----	DID NOT REMOVE ALL PAINT
"	65 IPM	-----	DID NOT REMOVE ALL PAINT

Conclusions:

1) By narrowing the spacing between passes from 2-1/2" to 2-1/4", the 1/2" unstripped region was eliminated. To reduce the spacing any further would be undesirable because it would reduce the paint removal rate.

2) The 2-1/4" spacing between robot passes may not be optimal, but at least it works. It is much easier to adjust robot velocity or nozzle pressure than to adjust spacing.

3) Due to the difficulty of the substrate and/or the coating, a 20 PSI nozzle pressure was inadequate, even with reduced robot velocity. An increase in nozzle pressure was necessary.

Date: 3/25/87

Purpose:
1) To maximize paint removal rate (within constraints) on an easy F-4 turtleback test panel
2) To determine the approximate maximum paint removal rate per nozzle for aluminum aircraft surfaces within robot velocity constraint of 200 IPM and nozzle pressure of 30 PSI

Equipment:
Schmidt PMB-BV Blast System
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
250 CFM compressor
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
Test panel: F-4 turtleback

Procedure: Same as on previous tests (3/24/87)

TABLE A-21. PAINT REMOVAL OPTIMIZATION ON AN EASY F-4 TURTLEBACK

Fixed Conditions:
Stand-off - 24"
Media valve opening - 7 turns
Spacing between passes - 2-1/4"
Number of passes in robot program - 6

NOZZLE PRESSURE	ROBOT VELOCITY	PAINT REMOVAL RATE	COMMENTS
30 PSI	100 IPM	1.91 FT^2/MIN	REMOVED PAINT/PRIMER COMPLETELY
"	150 IPM	2.60 FT^2/MIN	REMOVED PAINT/PRIMER COMPLETELY
"	200 IPM	2.92 FT^2/MIN	REMOVED PAINT/PRIMER COMPLETELY

Conclusions:
1) The maximum paint removal rate for this turtleback was 2.92 ft^2/min and the settings were at the respective limits; i.e. 30 PSI and 200 IPM.

2) The approximate maximum paint removal rate for one nozzle for aluminum aircraft surfaces is 2.92 ft^2/min.

Date: 3/26/87

Purpose:
1) To maximize the paint removal rate for a graphite composite panel without damaging the fibers.
2) To determine the approximate maximum paint removal rate for one nozzle on graphite composite aircraft surfaces without damaging the fibers.

Equipment:
Schmidt PMB-BV Blast System
Cincinnati Milacron T3-566 robot
1/2" blast nozzle
250 CFM compressor
U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness
Test panel: a 24" x 24" 8-ply unidirectional, graphite/epoxy composite test panel

Procedures: The paint is removed from a quadrant of a 24" x 24" composite panel as the robot travels back and forth over the quadrant in 6 passes with a spacing of 2-1/4" between successive passes. The actual stripped area is later measured. Robot velocity and/or nozzle pressure are readjusted as needed.

Results:

TABLE A-22. PAINT REMOVAL OPTIMIZATION ON GRAPHITE/EPOXY COMPOSITE TEST PANELS

Fixed Conditions:
Stand-off - 24"
Media valve opening - 7 turns
Spacing between passes - 2-1/4"
Number of passes in robot program - 6

NOZZLE PRESSURE	ROBOT VELOCITY	PAINT REMOVAL RATE	COMMENTS
30 PSI	100 IPM	1.59 FT^2/MIN	STRIPPED PAINT & PRIMER COMPLETELY; SOME APPARENT FIBER DAMAGE
30 PSI	150 IPM	----	DID NOT STRIP PAINT/PRIMER COMPLETELY
20 PSI	100 IPM	----	DID NOT STRIP PAINT/PRIMER COMPLETELY
20 PSI	75 IPM	1.29 FT^2/MIN	REMOVED PAINT & PRIMER COMPLETELY; NO APPARENT FIBER DAMAGE
10 PSI	50 IPM	----	LEFT MUCH PAINT AND PRIMER BEHIND
10 PSI	25 IPM	.31 FT^2/MIN	STRIPPED ALMOST COMPLETELY; LEFT A LITTLE PAINT AND PRIMER

Conclusions:

1) The maximum paint removal rate without fiber damage for these composite test panels was 1.29 ft^2/min. The respective process settings were 20 PSI and 75 IPM.

2) The approximate maximum paint removal rate per nozzle for graphite/epoxy composite aircraft surfaces without causing fiber damage is 1.29 ft^2/min.

3) It may be possible to strip composites at 30 PSI safely and thus more quickly than at 20 PSI, but a brief (one or two second) over-exposure at this pressure can cause fiber damage if the robot velocity is not perfectly controlled.

4) A brief over-exposure at 20 PSI is far less likely to cause fiber damage than at 30 PSI; thus, operating at 20 PSI is much safer than at 30 PSI.

Date:	3/26/87
Purpose:	1) To investigate the effect of compressed air sidestreams on the bead blast pattern. 2) To widen the swath width of the bead blast process.
Equipment:	Schmidt PMB-BV Blast System Cincinnati Milacron T3-566 robot 1/2" blast nozzle 250 CFM compressor U.S. Technology Polyplus media, 20/30 sieve size, 3.5 mohs hardness Test panel: F-4 turtleback
Procedure:	The robot is programmed to strip a single 39" long swath along the top of a turtleback. Streams of compressed air at 100 PSI through a nozzle and hose are directed at either sides of the bead blast system.
Results:	A small change (about 1/2" deflection) in the paint removal pattern was seen when compressed air was directed at the blast stream. No change in the pattern or increase in the "footprint" was observed.
Conclusions:	The 100 PSI sidestreams are insufficient to alter the paths of the plastic beads. The beads have too much momentum. This is not a viable way to effect the spray pattern unless pressure of the sidestreams is greatly increased.

APPENDIX B

PARAMETRIC BOUNDARIES
FOR
ACCEPTABLE PAINT REMOVAL RATES

The primary objective of Process Optimization is to provide data necessary to support design of the RPSC. The bottom line from an economic point-of-view is whether the system will be able to strip paint fast enough to be cost-effective. Imposed upon this requirement are the constraints of technical feasibility and the safety and protection of the substrate.

The first task to be accomplished in Process Optimization was to set up approximate boundaries for the process variables which would apply to our laboratory tests and to the actual built-and-installed paint stripper. We began by investigating the relationships between paint removal rate and all contributing variables.

From a mathematical point-of-view, paint removal rate is the linear product of robot velocity and swath width:

$$R = \frac{V \times W}{144}$$

where R = paint removal rate (ft^2/min)
V = robot velocity (inches/min)
W = swath width (inches)

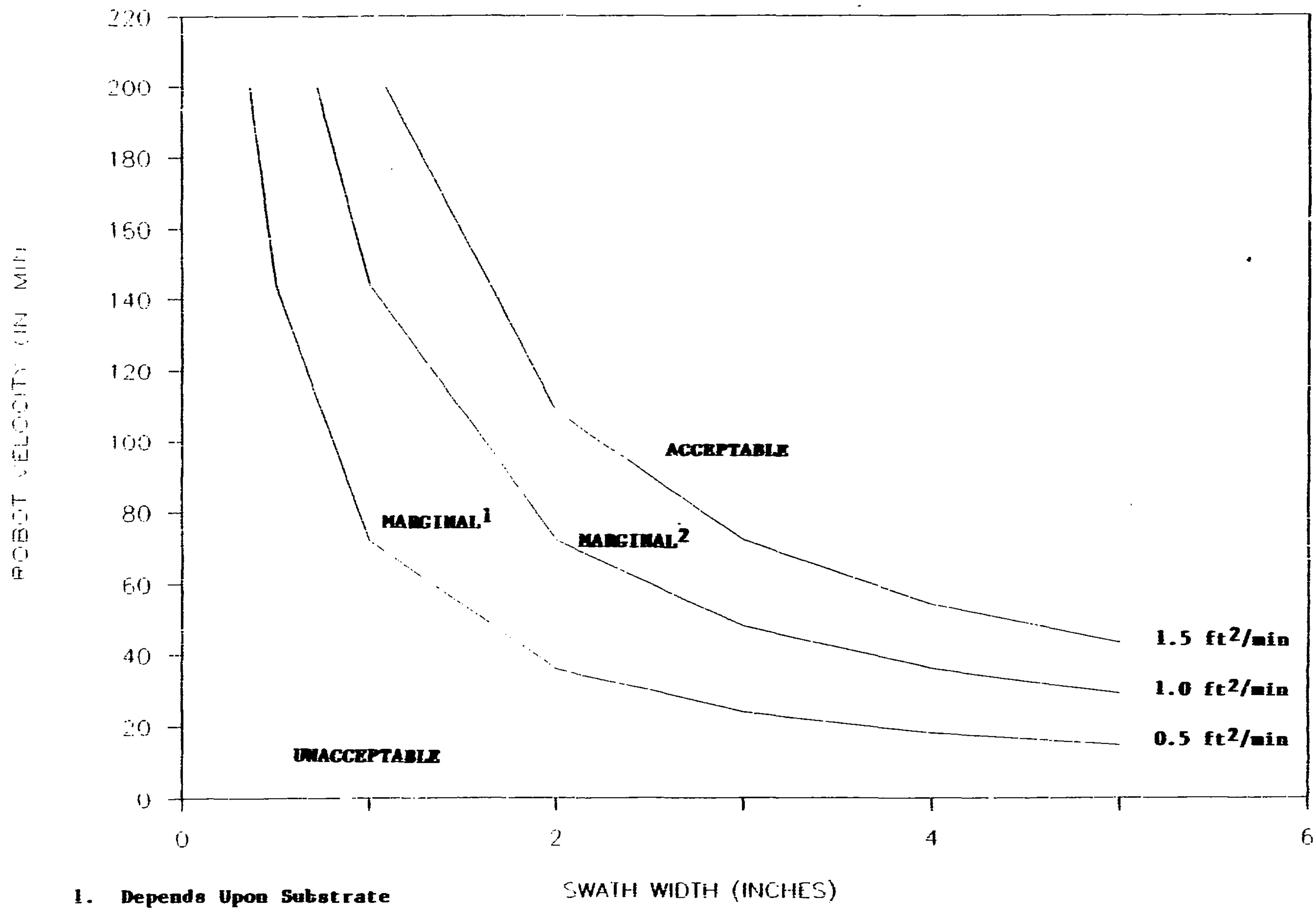
Robot velocity is an independent process variable which is programmed into the robot controller and is unaffected by all other variables. Swath width, however, is dependent upon all other process and equipment variables, in particular nozzle diameter, nozzle pressure, robot velocity, nozzle stand-off, and mass flow rate.

Between Applied Concepts Corp. and SwRI, it was determined that each nozzle of the RPSC must strip from 1.0-1.5 ft^2/min of painted aircraft surface (see Section 4.1). Anything below 0.5 ft^2/min was unacceptable. Rates between 0.5 and 1.0 ft^2/min are acceptable only under special circumstances (e.g. graphite composite surface). The acceptability of paint removal rates between 1.0 and 1.5 depends primarily on the number of nozzles, and anything over 1.5 ft^2/min is acceptable. This classification, along with the paint removal rate equation stated above, began to create an operating window for the process design variables. Figure B-1 "Acceptable Paint Removal Rates" illustrates the various regions of this operating window. The boundaries of this window were determined in the following way. The robot design team determined that the maximum limit of robot velocity is 200 inches/minute due to the size and performance constraints of the mechanized actuators. On the basis of previous data and our earliest experiences in plastic media paint stripping, a 5" swath is larger than the best swath width to be expected from one nozzle. At 0.5 ft^2/min and a 5" swath width, the precise calculated value for robot velocity is 14.4 in/min. We rounded that up to 25 inches/min for practicality and ease of robot programming, and it became our minimum acceptable robot velocity.

Swath width itself is not an independent process variable. We chose nozzle pressure, therefore, as the other most important variable to be optimized and

Figure B-1

ACCEPTABLE PAINT REMOVAL RATES



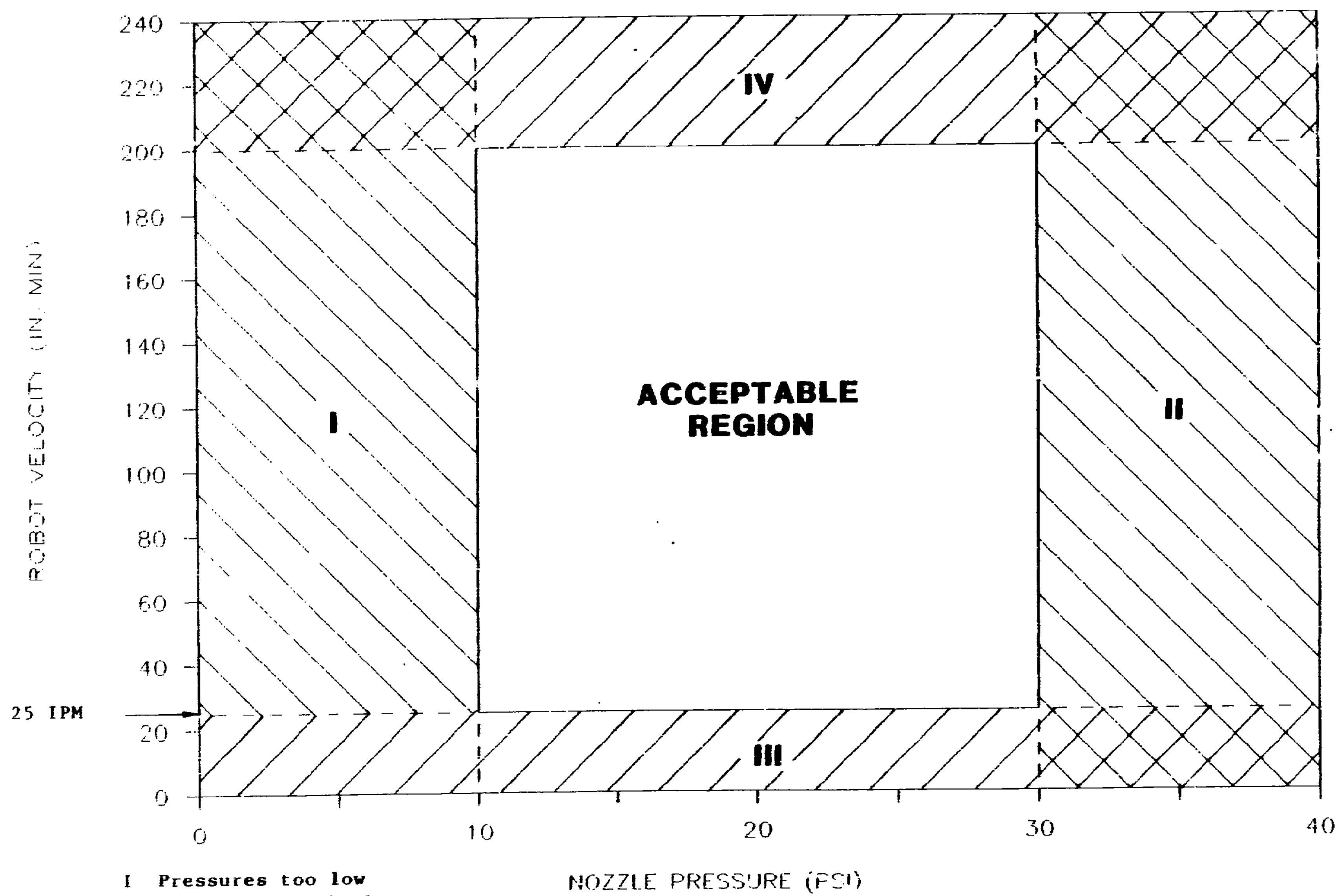
1. Depends Upon Substrate
2. Depends Upon Number of Nozzles

controlled. To do this, it was necessary to substitute nozzle pressure for swath width and then draw our parametric boundaries.

Most military aircraft paint stripping uses 20-45 PSI, and thus we began our tests within that range. Section 5.5 describes the process by which our experience showed us that we can reach adequate paint removal rates between 10-30 PSI and still be reasonably assured that we were not causing substrate damage. Thus the entire operating window of robot velocity and nozzle pressure shown in Figure B-2 was established and ready for optimization tests.

Figure B-2

PARAMETRIC BOUNDARIES



I Pressures too low
II Pressures too high
III Robot velocities too low
IV Robot velocities too high

APPENDIX C

ECONOMIC ANALYSIS AND BENEFITS ASSESSMENT (Excerpt)

Robotic Paint Stripper Cell
Phase III
Economic Analysis and Benefits Assessment Final Report

August 1990

Submitted to:

Southwest Research Institute

under

Prime Contract No. F33615-86-C-5044

Submitted by:

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Table of Contents

List of Figures

Robotic Paint Stripper Cell
Phase II
Economic Analysis and Benefits Assessment - Revised

I. Introduction

In July 1987 the "Preliminary Economic Analysis and Benefits Assessment of the Robotic Paint Stripper Cell (RPSC)" (Air Force under Contract No. F33615-86-C-5044) was presented. That report summarized the investigations and analyses that had been conducted by Applied Concepts Corporation under subcontract to Southwest Research Institute (SwRI).

Economic analysis has been an integral part of this technology development program. The preliminary economic analysis and benefits assessment and subsequent revisions were performed to establish cost objectives for the robotic system, to identify opportunities for cost savings, and to provide feedback on how well cost goals were being met. The intent of this aggressive economic analysis aproach was to maximize the liklihood that the project would yield a system that not only is technically excellent, but which makes economic sense to implement at Ogden Air Logistics Center (OO-ALC) and other ALCs.

Based upon a number of important assumptions and the information available at that time, the preliminary economic analysis and benefits assessment estimated that the savings realized in robotically stripping F-16s would be about five times greater than robotically stripping F-4s. The AFLCR 78-3 analysis found the present value of the RPSC investment over its projected ten year life to be more than $9 million. The savings to investment ratio was projected to be 3.97, and the payback period was slightly more than one and one-half years.

The latest revision of the preliminary economic analysis was presented in June 1989. This analysis projected that the ratio of savings realized for robotically stripping an F-16 versus an F-4 had been reduced from 5 to 2. The AFLCR 78-3 analysis indicated the savings-to-investment ratio increased slightly to 4.45, and the payback period dropped slightly to 1.39 years.

Sensitivity analyses were performed by adjusting several parameters considered to be most critical to the analysis. None of the assumed risks, including a combination of the two worst, caused the economic picture to become unattractive.

In summary, it has been projected throughout the project that the Robotic Paint Stripper Cell as designed by SwRI and applied to the projected OO-ALC workload, provides a significant opportunity for reducing the cost of stripping paint from fighter aircraft at OO-ALC, with minimal economic risk. Since the June 1989 revision, several of the parameters that made up the economic analysis and benefits assessment have changed -- some significantly. This report will discuss those changes and present their impact on the benefits analysis. In addition, this report is intended to establish the baseline for the Benefits Tracking Program that will be implemented when the RPSC is installed at OO-ALC. Some of this report will contain a review of what led up to the results described in previous analyses. This review is necessary to maintain an historical perspective on the development of the technology and its proposed insertion into repair operations at OO-ALC.

The reader is cautioned to keep in mind two important caveats when interpreting the results of this latest economic analysis and benefits assessment. First, only those benefits that could be quantified and monetized were considered in the analysis. Some very important benefits which are expected from the robotic system, such as reductions in damage to the substrate and the removal of personnel from the paint stripping environment, were not included in the analysis. Secondly, the baseline process of manual bead blast paint stripping has gone through about a four year optimization process. It is likely that improvements to the robotic system's operational efficiency will also take place over time, although we have not estimated them at this time.

II. Background

Paint is applied to the external surfaces of aircraft for corrosion control. In order to maintain the integrity of the corrosion control, it is necessary to periodically repaint the aircraft. Each new layer of paint adds weight to the aircraft and detracts from its performance. Each aircraft receives Programmed Depot Maintenance (PDM) at planned intervals during which, among other things, the aircraft is inspected for the need to be repainted. If painting is necessary, the external surfaces of the aircraft are usually stripped to the bare substrate, removing all paint. This process removes on the average five to seven layers of paint and until recently has been a costly, time-consuming, and hazardous process.

When this analysis was originally performed in 1896-87, the methods for removing paint from F-4 aircraft at Ogden Air Logistics Center (OO-ALC) (F-16s were not being stripped yet) were actually combinations of three different processes: hand sanding, chemical agents, and plastic media blasting.

The primary method for removing paint traditionally had been by the use of chemical solvents. Over the years, harder-to-remove paints and increased environmental and health restrictions reduced the effectiveness of chemical strippers. This required the addition of extensive abrasive sanding operations using hand tools. The stripping process, already labor intensive, became an increasingly difficult procedure that still had unacceptable environmental and health hazards.

Because of the increasing costs and hazards associated with chemical stripping, OO-ALC developed and installed a safer and more efficient means of stripping paint from F-4 aircraft using a pressurized blasting process with small plastic beads as the blast media. This manual blasting process became operational in 1986 and has been successful in effectively and efficiently removing paint.

III. Robotics Application Program

In 1985 the Air Force began a RepTech program to spur the implementation of robotics technology at the Air Logistics Centers (ALCs). The program's premise is that over the long term, the effective use of robots and robotic technology in the automation of maintenance and re-manufacturing processes is a key to ALC productivity enhancement.

The Robotic Paint Stripper Cell (RPSC) project within that program is to develop and implement an automatic, non-chemical means of stripping paint from F-4 and F-16 aircraft. The robotic system was intended to replace the remaining chemical stripping and provide economic and operational advantages over the new manual bead blast process. The RPSC project evaluated alternative paint removal processes, and chose the best one for integration into a robotic system capable of stripping entire fighter aircraft.

IV. Economic Analysis and Benefits Assessment

A. Description

The Robotic Paint Stripper Cell program included an aggressive economic analysis and benefits assessment that would help to maximize the likelihood that the project would yield a cost-effective system which can and will be implemented. It was to do this by:

1) The establishment of cost targets early in the program which the new process would have to beat. The cost targets were based upon the costs of the baseline process.

2) The early establishment of cost tracking and reporting procedures and responsibilities for cost reporting and other data requirements.

3) The performance of periodic cost reviews, and continuous feedback from the economic analyses to the project manager, to provide ongoing knowledge of whether cost goals are being met, and to provide the basis for redirecting the technical effort to meet cost targets.

4) The performance of comprehensive cost-benefits analyses at the end of Phase I (design) and Phase II (fabrication) which describe the expected economic payoffs, and which would be considered by the Air Force in deciding whether or not to proceed to the next phase.

The economic analyses performed thus far were done from two perspectives:

- Cost per aircraft analysis - Using ACC's COSTARGET methodology

- Analysis based upon AFLCR 78-3

B. COSTARGET

COSTARGET is the process that was used to establish cost targets early in the program that the new process would have to beat. The cost targets are based upon the costs of the baseline process, which for the purposes of this analysis is the existing bead blast stripping process at OO-ALC.

The challenges in the use of cost targets over the life of this nearly four year project are to keep the targets meaningful and purposeful. This is accomplished by making the baseline *dynamic* - that is, by revising the baseline to incorporate changes in the process as they occur. While a dynamic baseline may give the design team a moving target at which to shoot, it provides continuous guidance and direction to help ensure that the developed system will be cost-effective, and will "out compete" the baseline.

Three types of costs were considered in determining the cost target for the robotic paint stripping process at OO-ALC - - direct labor, material, and indirect costs. These costs were broken down further into the three portions of the paint stripping process - - pre-stripping operations, stripping operations, and post-stripping operations. The details for the derivation of these costs are presented in Appendix A .

It was confirmed that, as is the case with most robotic automation projects, the robot must be heavily utilized for the project to be cost-effective. If the automated system is underutilized (i.e., if the throughput/capacity ratio is low), then economic justification for the project is unlikely.

C. ALC-RIDM/AFLCR 78-3 Analysis

AFLCR 78-3 is the Air Force Logistics Command regulation that governs how investment analyses at the ALCs must be performed and presented. To assist in performing the economic analysis, a computerized analysis tool was used called ALC-RIDM (Air Force Logistics Command - Robotics Investment Decision Model). ALC-RIDM was developed by Applied Concepts Corporation in another Rep Tech program specifically to meet the requirements of AFLCR 78-3. The user provides certain input information such as economic life and discount rate, and performs "As-Is" and "To-Be" calculations of the costs of the current and proposed systems. The model then computes:

- Net Present Value of the Savings Produced by the Investment

- Savings-to-Investment Ratio

- Amortization or Payback Period

ALC-RIDM was found to be an extremely useful tool for analyzing the economics of the Robotic Paint Stripper Cell. It was valuable in providing the baseline analysis for comparing the investment strength of the proposed system, plus it provided the necessary flexibility for performing sensitivity analyses by allowing adjustments to the baseline assumptions. The worksheets and outputs from this model are included in Appendix C.

D. Assumptions

The Preliminary Economic Analysis and Benefits Assessment presented in July, 1987 required a series of assumptions relative to two existing ("baseline") paint stripping processes (chemical and plastic media blasting). Because chemical stripping is no longer used for stripping whole aircraft at OO-ALC, it is not discussed in this report and all assumptions regarding the baseline refer to the manual plastic media blasting process currently in use at OO-ALC.

Baseline assumptions were derived as a result of more than 300 man-hours of on-site investigation at OO-ALC. Meetings were held with personnel in industrial engineering, production engineering, time standards engineering, quality control, bio-environmental and civil engineering, and safety engineering, as well as with paint shop production operators, supervisors, and operators.

1. Facility

It was assumed that the robotic paint stripping cell would be installed in the original bead blast facility for whole aircraft at OO-ALC (Building 223). This is the current project plan. It minimizes additional capital expense and limits the impact on OO-ALC's production facilities during installation. Only minimal modifications to the existing structure are needed to provide for installation of the robotic cell. The cost of these modifications is included in the economic analysis. In addition, modifications to the existing bead blast system to bring its performance up to the level of performance of other manual facilities are necessary before the RPSC can be installed. These costs are not included in this analysis since they would also be needed for a manual system.

The capital cost of the existing facility was not included in this economic analysis, for either the "As-Is" or the "To-Be." This is a change from the earlier analyses. This was done because the difference in cost between a manual plastic media blasting facility and one built specifically for an automated system is essentially negligible. This analysis is intended to determine the economic viability of inserting the RPSC technology into the production system at OO-ALC, where both the currently used manual PMB facility and the RPSC facility represent sunk costs.

2. Workload

At the time this contract began (April, 1986) the annual paint stripping work load at OO-ALC was forecast by OO-ALC/MABEC to be approximately 200-225 F-4 aircraft annually for each of the next five years. There were no F-16 aircraft being processed through Programmed Depot Maintenance (PDM). Workload projections of F-16s to be stripped were not made at that time.

The workload projection has changed continuously throughout this project. The last analysis (June 1989) used workload rates for the years 1990 - 2000 of 105 F-4s and 178 F-16s annually. Shown below is a summary graph of the workload projections provided throughout the project. Forecasts were obtained from OO-ALC/MABEC.

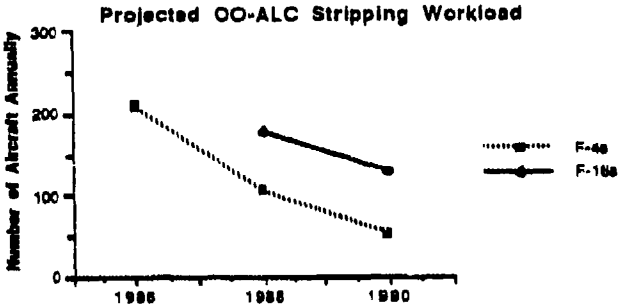


Figure 1.

As has been mentioned in earlier analyses, automation usually only pays off economically if it is extensively used. The continued erosion of the paint stripping workload at OO-ALC is a significant factor in reducing the viability of automating the paint stripping process. This baseline economic analysis assumes that the average paint stripping workload for F-4 and F-16 aircraft at OO-ALC for the ten year period 1991 - 2001 will be 52 and 130 per year, respectively. Again, these numbers are based on OO-ALC/MABEC's latest estimate.

3. Labor Rates

We have employed the FY90 labor rate prescribed by HQ-AFLC/MAQF for AFLCR 78-3 analyses. These are the average labor rates for each ALC (see Appendix B). AFLC requires their use in economic analyses to ensure results are comparable across ALCs. The FY90 labor rate prescribed by HQ-AFLC/MAQF for OO-ALC is $19.16/hour.

During the analysis of alternative paint stripping processes, we determined that most plant overhead type costs would not be affected by automation. Actual indirect costs that would be affected were estimated and directly included in the economic analysis. Therefore, a direct labor rate was used which included direct labor and benefits, but not any overhead loading.

4. Material Costs

One of the important cost elements of plastic media blasting, both manual and automated, is the cost of direct material, primarily plastic media. The cost of material in this analysis is assumed to remain constant over the 1991 - 2001 period of analysis. Our analysis shows that material costs have been relatively stable over the last several years with a trend toward lower prices.

One factor that will affect plastic media costs (and waste disposal costs) is the possibility of "leasing" the blast media from the manufacturer. For a higher "per pound" price, OO-ALC would use the media for a leased price, and the manufacturer would pick up the used media and fines. The manufacturer would then be responsible for proper disposal of the spent material. This purchasing option has not been exercised yet, although we encourage its use in both manual and robotic processes.

5. Flow Time Costs

This economic analysis includes the cost of temporarily removing the aircraft from service, per AFLC guidance and per common practice across most of the ALC's. We call these costs "flow day" costs because they vary directly with the amount of time an aircraft remains out of service, which in the case of the ALC's is the amount of time it takes to perform the maintenance work.

Our previous economic analyses considered flow day costs using one of several commonly used methods. Since the earlier analyses, an Air Force approved method for calculating flow day valuations was identified. It was developed at Hill AFB by the 2849th ABGp/COMPTROLLER/ACM MANAGEMENT and COST ANALYSIS BRANCH. This method caused the flow day valuations for both aircraft types to increase significantly. For the F-4 it increased from $2,098 per day to $8,575 per day. The F-16 flow day valuation increased from $5,125 to $31,710 per day. This increase causes flow time costs to become an overwhelming cost driver in comparison to all other costs. This will be explained in more detail later.

6. Two Shift Operation of the Paint Stripping Cell

While the OO-ALC paint stripping organization has the capability to run three shifts with both manual and robotic processes, for the purposes of this analysis, a two shift operation is assumed. One reason for this choice is that planned periodic maintenance will need to be performed during the "off shift". Another reason is that three shift operation is not a common practice at OO-ALC or other ALCs.

7. Stripping of Composites

Manual plastic media stripping of composite substrates is a standard practice at OO-ALC and, we assume, will also be performed by the RPSC. This was also assumed on the earlier analyses.

8. Paint Stripping Rate

Based upon testing at Southwest Research Institute, a paint removal rate of 2.5-5.0 ft^2 per minute per robot can be achieved. The average rate over the entire aircraft will not be substantiated until full system tests are conducted during Phase III. However, based upon all testing of the process to date, the development team believes that an average rate of 4.0 ft^2 per minute per robot is a reasonable assumption for this analysis.

9. Machine Availability

A machine availability factor of 85% was used for this analysis. This means that of the planned two shifts of operation (4160 hours annually), the system will be available to strip aircraft for 3536 of those hours annually.

10. Cell Efficiency

A cell efficiency factor of 85% was used for this analysis. Cell efficiency is a measure of how efficiently the work load can be managed. At 100% efficiency, an aircraft always would be available for placement in the Robotic Paint Stripping Cell as soon as the previous aircraft is finished. It was assumed that this would be the case only 85% of the time.

E. Process/Application Characterization

In order to develop the required depth of understanding for the economic analysis of the proposed automation project, it was necessary to determine the cost structure of aircraft paint stripping. This required defining and understanding all of the steps that are necessary to remove the coatings from an aircraft. While this understanding is intended to be independent of the means used to remove the coatings, obviously it can only be done by studying the processes that are being used.

Several trips were made to OO-ALC during Phases I and II to work on-site in paint stripping facilities to study how aircraft are stripped, why it is done the way it is, and where the money goes. During these trips a great deal of process information, industrial engineering data, and economic data was obtained, and the existing paint stripping operations at OO-ALC were characterized in detail. Details of manual bead blast stripping process and associated costs are contained in Appendix A.

The original analytic effort focused on the internal dynamics of the individual work cell. The only assumption made regarding work load at this stage was that the work cell was fully utilized. Thus, this analytic step provided a "workload-neutral" assessment of the costs, and costs were expressed in terms of "cost per aircraft."

The earlier analysis determined the major tasks of each process, the major cost drivers within each process, and the relative advantages and disadvantages of each. It provided important clues for r .aximizing the cost effectiveness of robotic paint stripping.

The process of paint stripping was broken down into three basic steps:

- Pre-strip Operations
- Strip Operations
- Post-strip Operations

Each of these steps was broken down further into sub-steps as shown in Figure 2. These sub-steps were then examined in detail through discussions with paint stripping personnel, paint stripping supervisors, and engineering personnel to determine the time and costs associated with each step. Based upon these investigations, the information was expanded and presented in the form of Figure 3 for each of the tasks being considered:

- manually stripping F-4s
- manually stripping F-16s
- robotically stripping F-4s
- and robotically stripping F-16s.

A summary of the cost analysis comparing manual and robotic bead blast systems is presented in Figure 4.

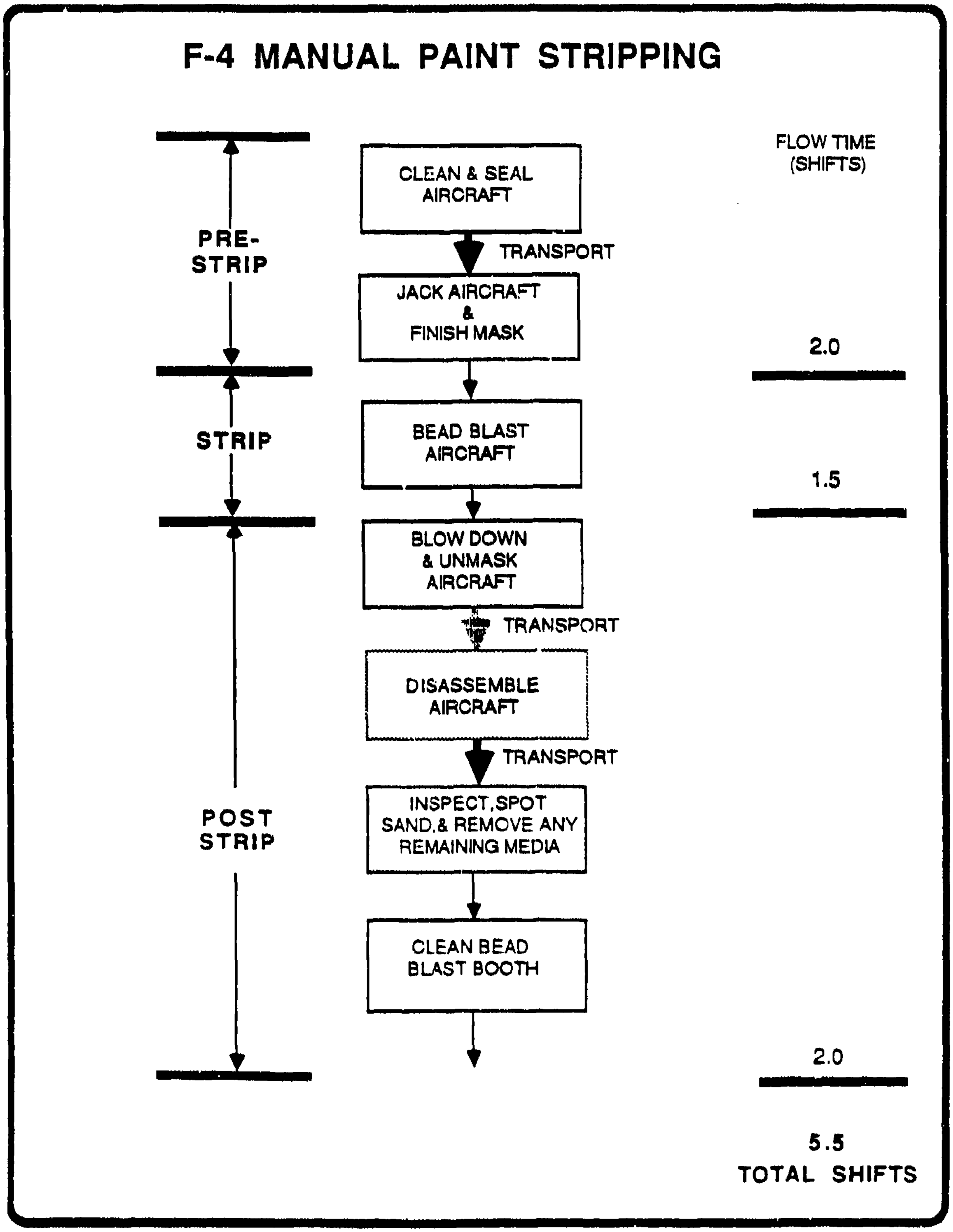
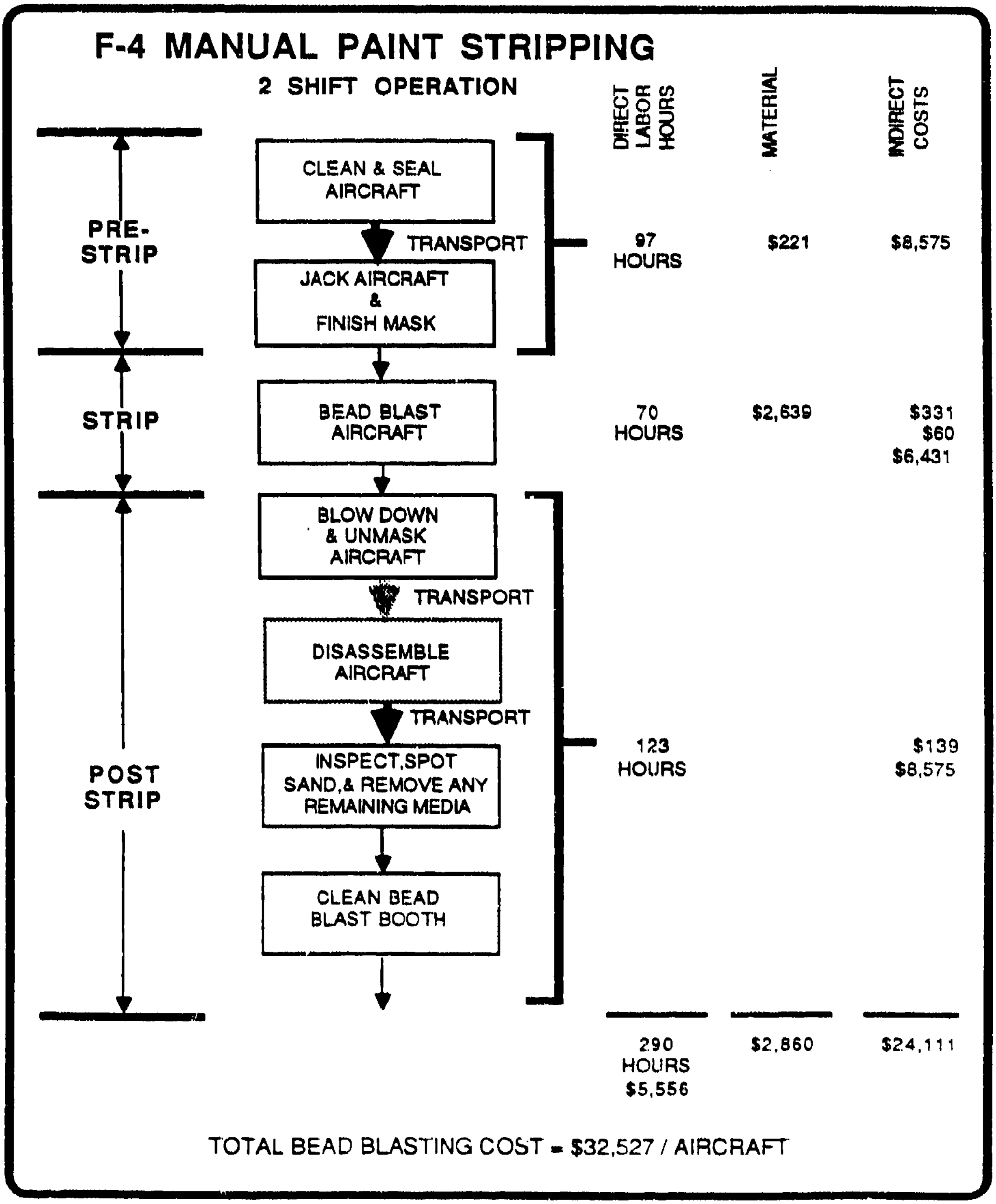
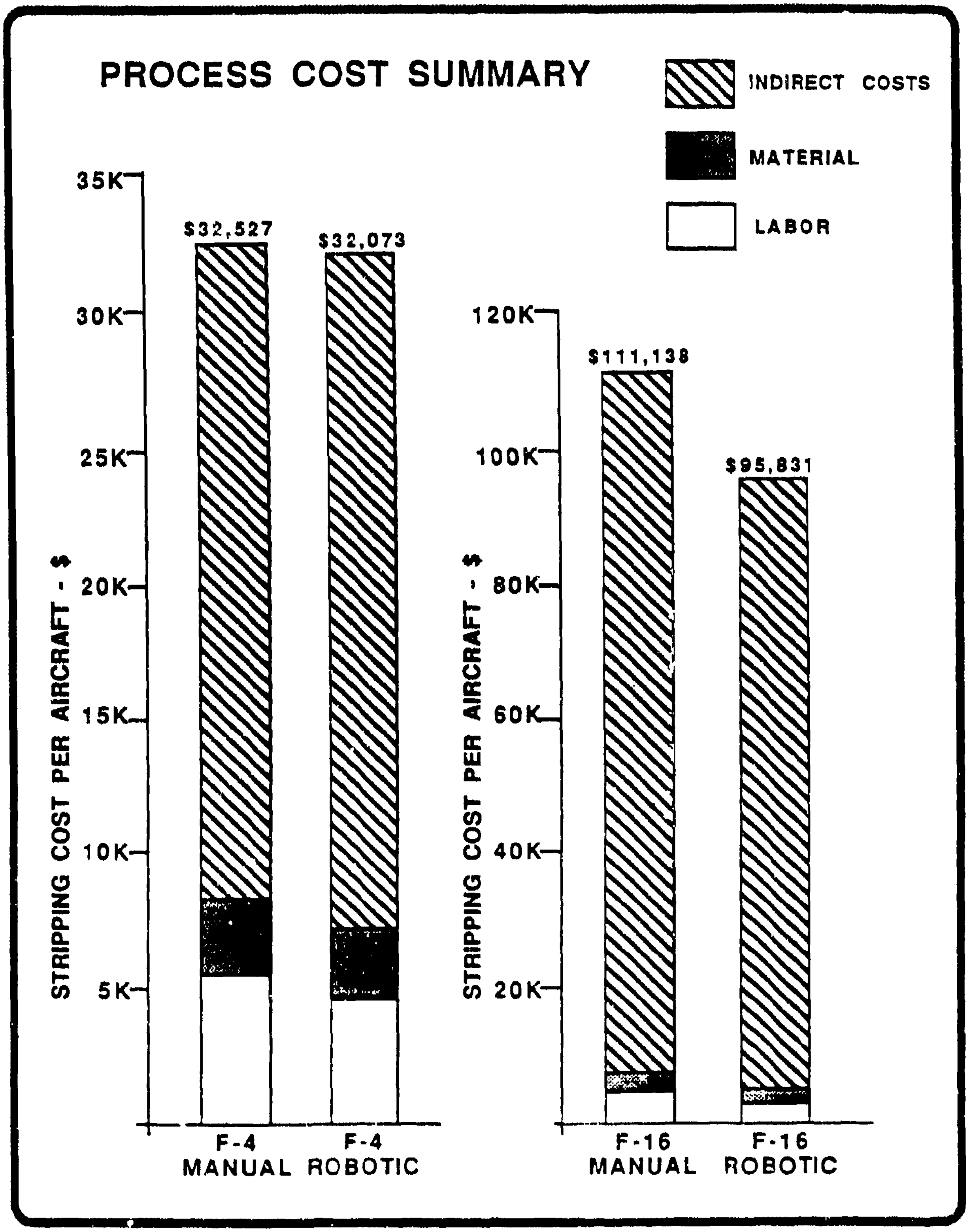

F-4 MANUAL PAINT STRIPPING
PRE-STRIP
STRIP
POST STRIP
CLEAN & SEAL AIRCRAFT
TRANSPORT
JACK AIRCRAFT & FINISH MASK
BEAD BLAST AIRCRAFT
BLOW DOWN & UNMASK AIRCRAFT
TRANSPORT
DISASSEMBLE AIRCRAFT
TRANSPORT
INSPECT,SPOT SAND,& REMOVE ANY REMAINING MEDIA
CLEAN BEAD BLAST BOOTH
FLOW TIME (SHIFTS)
2.0
1.5
2.0
5.5 TOTAL SHIFTS

Figure 2



F-4 MANUAL PAINT STRIPPING
2 SHIFT OPERATION
DIRECT LABOR HOURS
MATERIAL
INDIRECT COSTS
PRE-STRIP
CLEAN & SEAL AIRCRAFT
TRANSPORT
JACK AIRCRAFT & FINISH MASK
97 HOURS
$221
$8,575
STRIP
BEAD BLAST AIRCRAFT
70 HOURS
$2,639
$331
$60
$6,431
POST STRIP
BLOW DOWN & UNMASK AIRCRAFT
TRANSPORT
DISASSEMBLE AIRCRAFT
TRANSPORT
INSPECT,SPOT SAND,& REMOVE ANY REMAINING MEDIA
CLEAN BEAD BLAST BOOTH
123 HOURS
$139
$8,575
290 HOURS
$5,556
$2,860
$24,111
TOTAL BEAD BLASTING COST = $32,527 / AIRCRAFT

Figure 3



PROCESS COST SUMMARY
INDIRECT COSTS
MATERIAL
LABOR
35K
30K
25K
20K
15K
10K
5K
STRIPPING COST PER AIRCRAFT - $
$32,527
$32,073
F-4
MANUAL
F-4
ROBOTIC
120K
100K
80K
60K
40K
20K
STRIPPING COST PER AIRCRAFT - $
$111,138
$95,831
F-16
MANUAL
F-16
ROBOTIC

Figure 4.

This analysis shows that the economics of manual and robotic bead blast stripping are very sensitive to the type of aircraft being stripped. Note the difference between manual and robotic stripping costs for each of the two aircraft. The difference for an F-4 is less than $500 while the difference for an F-16 is more than $16,000. This means that the payoff from automation will be greater if the robotic cell concentrates on stripping F-16's, with excess cell capacity or slack time used for stripping F-4's.

F. Cost Drivers Analysis

It can be seen in Figure 4 that indirect costs are the largest component of the total costs for any of the scenarios. In order to understand what comprises these indirect costs they were broken down and presented in Figure 5.

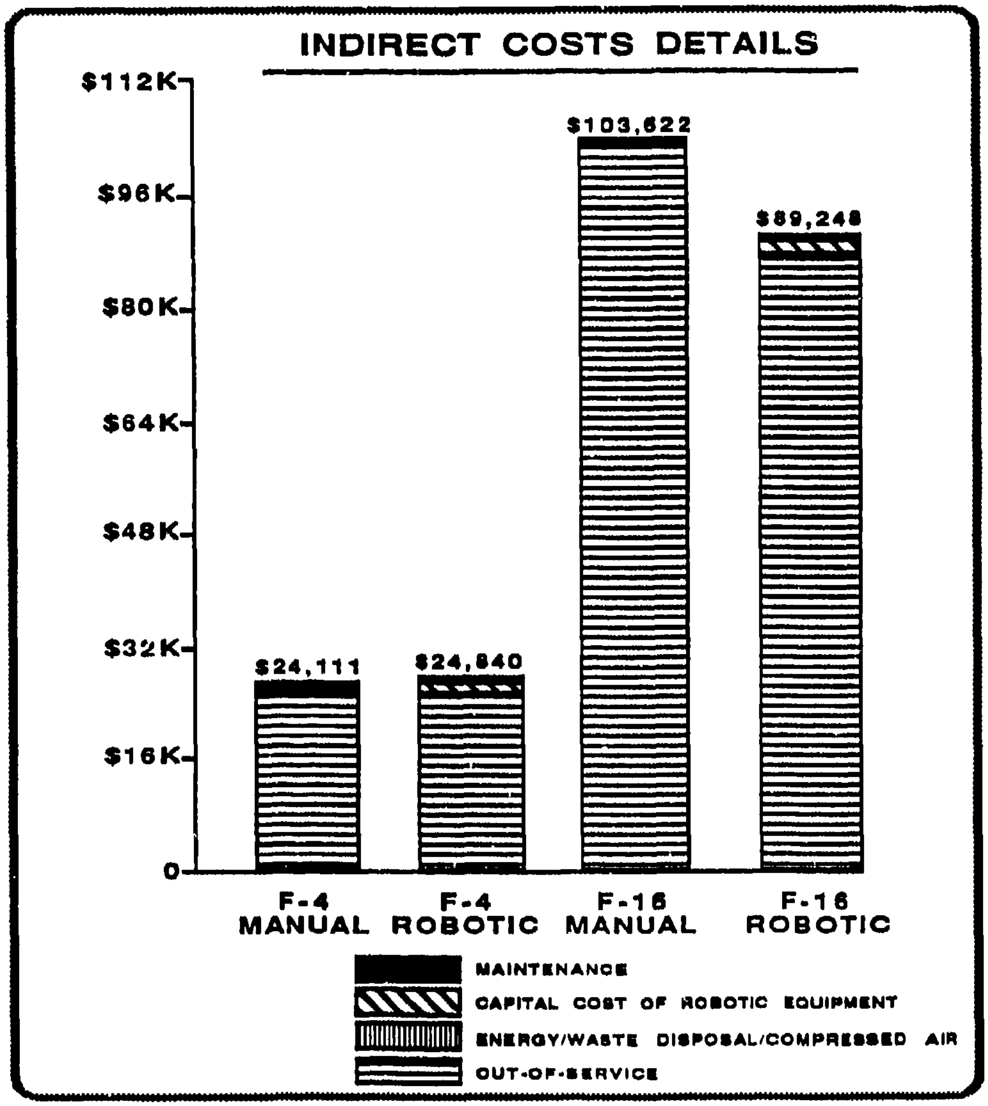


Figure 5.

There are two major changes in the accounting of indirect costs since the June 1989 revision. These relate to the out-of-service costs and the costs for compressed air.

In the June 1989 revision, the cost for compressed air was added to the analysis. This air is used by personnel within the paint stripping booth while operating the PMB hoses and is used for breathing and cooling in special suits designed for thiS purpose. OO-ALC has a central compressor room that provides clean compressed air through piping to areas that require it. The costs for this air were not available from OO-ALC, and the June 1989 analysis estimated these costs based upon estimates derived in similar ALC applications, specifically, the fuel tank desealing operation at SM-ALC. The SM-ALC operation does not use centrally sourced breathing air, but rather uses refillable bottles. The cost per shift per man in this operation, it turns out, are significantly higher than a centrally sourced breathing air operation. The OO-ALC costs have been derived based upon data taken since June 1989. The June 1989 estimate has been reduced from $975 per aircraft stripped to $60. This has removed more than $900 in projected savings per aircraft.

Obviously, the out-of-service costs overwhelmingly make up the greatest portion of the indirect costs. This has been magnified since using the method prescribed by OO-ALC. These costs are considered to be real costs to the USAF and any reduction in them is considered to be a true cost savings. However, many persons in the Air Force argue that it is dangerous to base ALC investment decisions on aircraft out-of-service savings because these savings rarely are actually realized. Therefore, it is important to evaluate aircraft paint stripping without consideration of out-of-service costs. Such a comparison is shown in Figure 6.

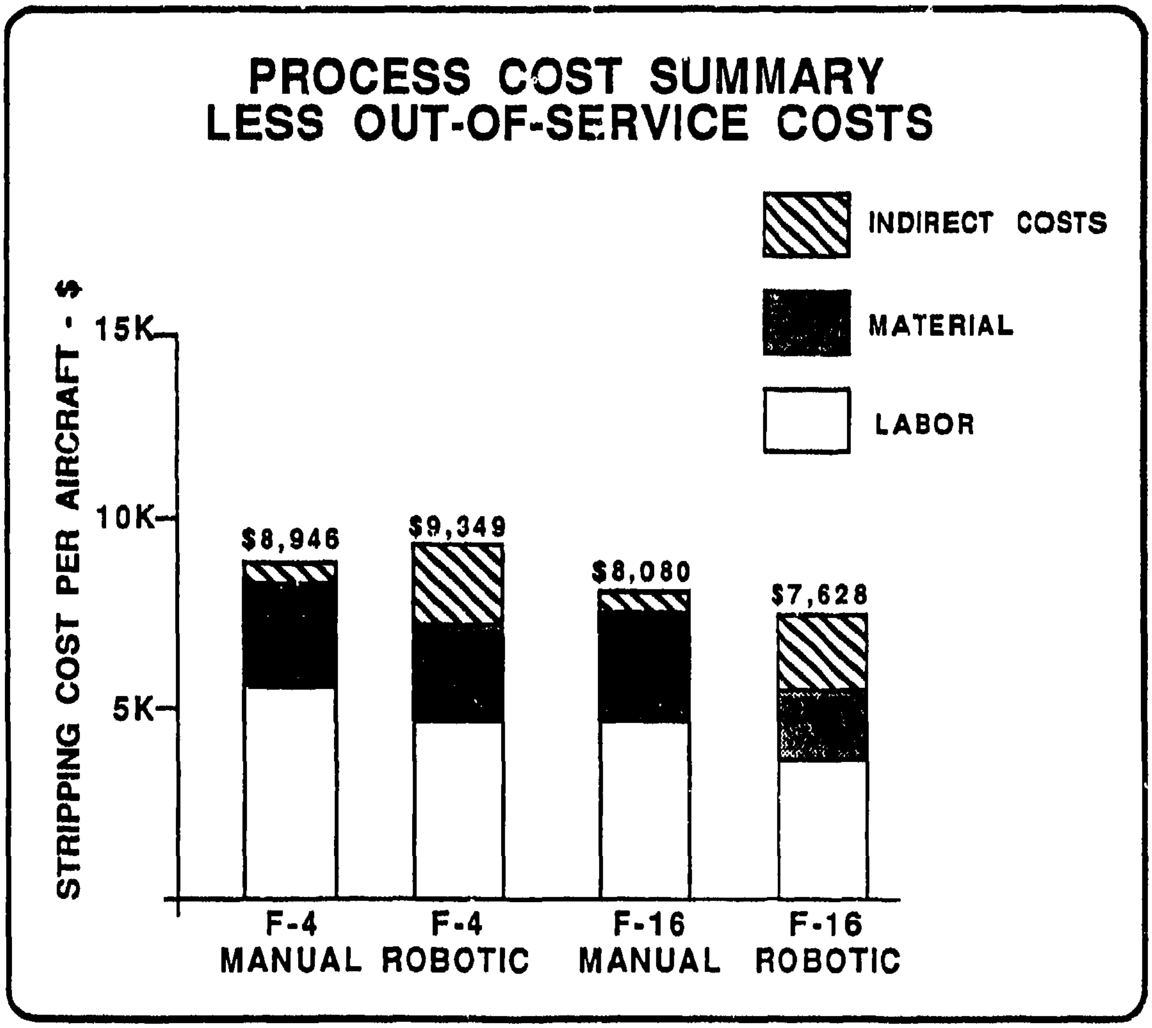


Figure 6.

The economic picture changes significantly when out-of-service costs are not considered. It is no longer projected that a savings will be realized when stripping an F-4 and projected F-16 savings are reduced to approximately $400 per aircraft stripped. Aircraft out-of-service costs account for more than 70% of the total cost for stripping an F-4 and more than 90% of the total cost of stripping an F-16. Very slight changes in flow day estimates for any of the scenarios cause radical changes in the economic attractiveness of the RPSC.

The flow time for the actual stripping of the aircraft, that is, that portion of the process that automation can affect, is only 1.5 to 2 shifts. This is not a significant amount of time for automation to change. Most major operations at the ALCs customarily take place in one shift increments. Lowering the paint stripping flow time below one shift is not realistic.

The estimates here project an out of service improvement of only 4% for the F-4 and only 15% for the F-16. These are very small improvements, not proven by actual experience. Because they are both uncertain and account for such a large percentage of the savings (reduction), one could argue that the economic attractiveness of the RPSC should not be based on them alone.

The choice for using or not using out-of-service costs will be left up to the customer. Both analyses will be presented.

An additional factor in reducing the economic attractiveness of the RPSC since June 1989 has been a reduction in the required number of man-hours for manually stripping an aircraft. Since June 1989, the required man-hours for stripping both F-4s and F-16s have been reduced from 97 to 70 (a 28% improvement). OO-ALC production personnel stated that this number could be reduced even further in the near future.

G. Integration of Workload and Application/Process

The next step in the economic analysis was to integrate the workload at OO-ALC and the Robotic Paint Stripping Cell design in order to:

- Estimate the workload capabilities of the "AS-IS" and the "TO-BE".

- Apply the workload and perform AFLCR 78-3 economic analyses.

Figure 7 below compares the projected workload at OO-ALC for both types of aircraft with the throughput capability of a manual and robotic bead blast cell.

THROUGHPUT CAPABILITY
- 2 SHIFT OPERATION -
(at 85% machine availability and 85% efficiency)

	THROUGHPUT CAPABILITY MANUAL BEAD BLAST CELL	THROUGHPUT CAPABILITY ROBOTIC BEAD BLAST CELL
F-4	126 (4.1 in-cell shifts/aircraft)	133 (3.9 in-cell shifts/aircraft)
F-16	110 (4.7 in-cell shifts/aircraft)	147 (3.5 in-cell shifts/aircraft)

Figure 7.

The throughput capabilities in this figure were developed using an assumed 85% machine/cell availability

and an 85% cell efficiency.

By comparing the throughput capability with the workload requirements, it becomes apparent that neither a single manual cell nor a single robotic cell is capable of handling the combined F-4 and F-16 workload. However, two additional manual bead blast cells have been constructed at OO-ALC and are operational. With one robotic bead blast cell and the additional manual bead blast cells, the economically optimal allocation of the projected workload would be as presented in Figure 8 below.

OO-ALC WORKLOAD ALLOCATION

	TOTAL DEMAND (PROJECTED OO-ALC 1991 WORKLOAD)	ROBOTIC PAINT STRIP CELL	MANUAL BEAD BLAST
AS-IS	52 F-4's	-	52 F-4's
	130 F-16's	-	130 F-16's
TO-BE	52 F-4's	16 F-4's	36 F-4's
	130 F-16's	130 F-16's	-

Figure 8.

Using the existing manual bead blast process, all 182 aircraft could be done in two cells. Incorporation of the RPSC would provide the advantage of reducing stripping costs, but would also maintain full manual backup.

In the "To-Be" situation, all of the 130 F-16s plus 16 of the F-4s would be stripped in the robotic cell. This would leave 36 of the F-4s to be stripped in a manual bead blast cell.

Using this scenario, the AFLCR 78-3 analysis was performed using the ALC-RIDM computer model. Estimates of the fabrication and installation costs for the Robotic Paint Stripping Cell were provided by Southwest Research Institute. Those costs are shown below.

Two Robots & Associated Hardware		$2,037,568
Software Debug		12,590
Installation & Verification		78,784
Training		22,356
Documentation		13,670
Project Management		139,630
	Total	$2,304,598

These costs are only those associated with the actual fabrication and installation of the Robotic Paint Stripping Cell and do not include the one-time development costs or the data item and reporting costs associated with this project. As mentioned previously, also not included are the costs associated with the plastic media equipment or the building.

Figure 9 presents the results of the AFLCR 78-3 baseline analysis.

1. DATE	2. FISCAL YEAR	EQUIPMENT LINE ITEM DATA	3.DEPARTMENT	4.INSTALLATION
16-May-89	FY 89		MABPS	OO-ALC
5. LINE ITEM NUMBER 0		6. LINE ITEM TITLE AUTOMATED AIRCRAFT PAINT STRIPPING BASELINE ANALYSIS		

SUMMARY OF EQUIPMENT COSTS – FORMAT A

1.INVESTMENT	
A.ACQUISITION COST	$2,037,568
B.INSTALLATION COST	$78,784
C.OTHER COSTS	$188,246
D.TOTAL COSTS	$2,304,598
2.LESS TERMINAL(DISPOSAL) VALUE OF EXISTING EQUIPMENT	$0
3.NET INVESTMENT	$2,304,598
4.PRESENT VALUE OF BENEFITS	$38,076,476
5.SAVINGS/INVESTMENT RATIO	16.52
6.AMORTIZATION PERIOD	0.37 YEARS

SUMMARY OF EQUIPMENT BENEFITS – FORMAT B

1.PERSONNEL	PRESENT	PROPOSED	ANNUAL SAVINGS
A.CIVILIAN	$894,197	$540,456	$353,742
B.MILITARY	$0	$0	$0
C.OTHER	$25,291	$33,520	($8,229)
2.OPERATING			
A.MAINTENANCE	$33,233	$18,114	$15,119
B.UTILITIES	$562,956	$306,310	$256,645
C.OTHER	$29,247,400	$23,685,394	$5,562,006
3.OVERHEAD	$0	$0	$0
4.TOTAL ANNUAL SAVINGS			$6,179,283
A.PRESENT VALUE OF ANNUAL SAVINGS			$37,969,040
5.ONE TIME SAVINGS			$0
A.PRESENT VALUE OF ONE TIME SAVINGS			$0
6.TERMINAL VALUE OF PROPOSED EQUIPMENT			$278,664
A.PRESENT VALUE OF TERMINAL VALUE(.38554)			$107,436
7.TOTAL PRESENT VALUE OF BENEFITS			$38,076,476
8.ECONOMIC LIFE			10 YEARS
9.DISCOUNT FACTORS - 10%			4 - 6.1446 6 - 0.3855

10.EXPLANATION OF SOURCE/DERIVATION OF ESTIMATES:

AFLC FORM 177
SEP 71

Figure 9.

1. DATE 16-May-89	2. FISCAL YEAR FY 89	EQUIPMENT LINE ITEM DATA	3.DEPARTMENT MABPS	4.INSTALLATION OO-ALC
5. LINE ITEM NUMBER 0		6. LINE ITEM TITLE AUTOMATED AIRCRAFT PAINT STRIPPING BASELINE less OUT-OF SERVICE COSTS		

SUMMARY OF EQUIPMENT COSTS -- FORMAT A

1.INVESTMENT	
A.ACQUISITION COST	$2,037,568
B.INSTALLATION COST	$78,784
C.OTHER COSTS	$188,246
D.TOTAL COSTS	$2,304,598
2.LESS TERMINAL(DISPOSAL) VALUE OF EXISTING EQUIPMENT	$0
3.NET INVESTMENT	$2,304,598
4.PRESENT VALUE OF BENEFITS	$1,866,294
5.SAVINGS/INVESTMENT RATIO	0.81
6.AMORTIZATION PERIOD	8.05 YEARS

SUMMARY OF EQUIPMENT BENEFITS -- FORMAT B

1.PERSONNEL	PRESENT	PROPOSED	ANNUAL SAVINGS
A.CIVILIAN	$894,197	$540,456	$353,742
B.MILITARY	$0	$0	$0
C.OTHER	$25,291	$33,520	($8,229)
2.OPERATING			
A.MAINTENANCE	$33,233	$18,114	$15,119
B.UTILITIES	$562,956	$306,310	$256,645
C.OTHER	$0	$331,032	($331,032)
3.OVERHEAD	$0	$0	$0
4.TOTAL ANNUAL SAVINGS			$286,246
A.PRESENT VALUE OF ANNUAL SAVINGS			$1,758,858
5.ONE TIME SAVINGS			$0
A.PRESENT VALUE OF ONE TIME SAVINGS			$0
6.TERMINAL VALUE OF PROPOSED EQUIPMENT			$276,664
A.PRESENT VALUE OF TERMINAL VALUE(.38554)			$107,436
7.TOTAL PRESENT VALUE OF BENEFITS			$1,866,294
8.ECONOMIC LIFE			10 YEARS
9.DISCOUNT FACTORS - 10%			4 - 6.1446 6 - 0.3855

10.EXPLANATION OF SOURCE/DERIVATION OF ESTIMATES:

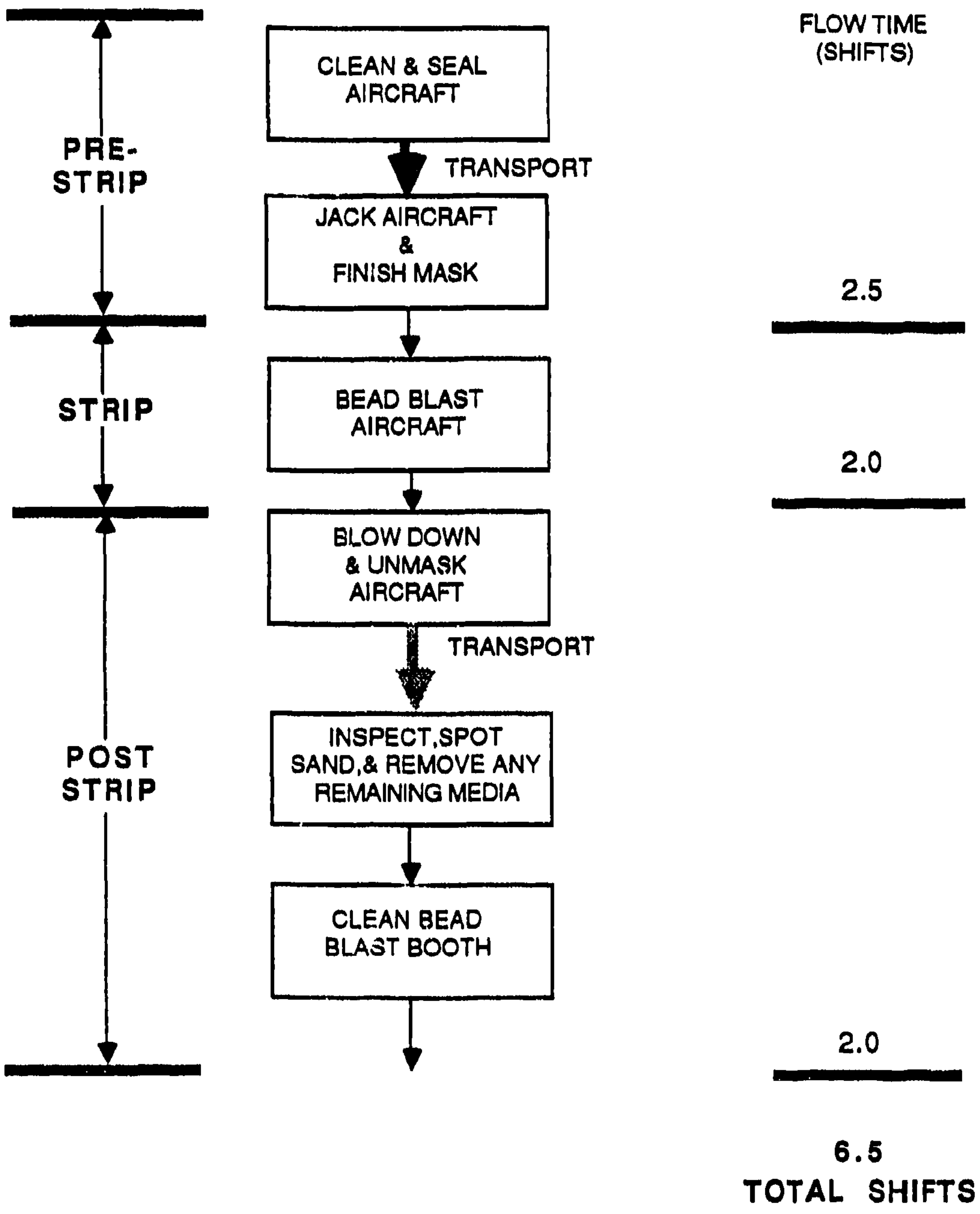
AFLC FORM 177
SEP 71

Figure 10.

Figure 8, which includes out-of-service costs, indicates that if the Robotic Paint Stripping Cell were implemented as described in Southwest Research Institute's Detailed Design Report, and was applied to the workloads described in this report, the present value of benefits over an assumed economic life of ten years would be in excess of $32 million. The savings/investment ratio is approximately 14 to 1 and the payback period for the investment is approximately one-half year.

Figure 9 which excludes out-of-service costs, results in a present value of benefits of approximately $1.9 million. The savings-to-investment ratio is only .81 and the amortization period is 8 years.

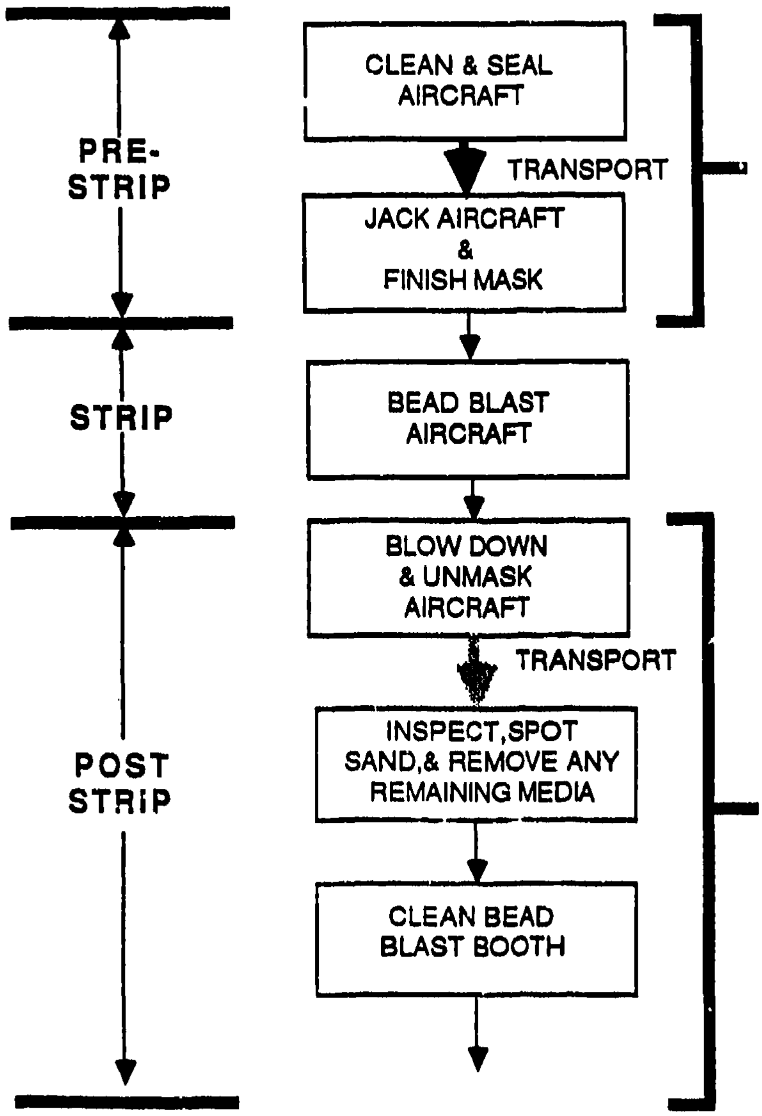
F-16 MANUAL PAINT STRIPPING



REVISED July 10, 1990

F-16 MANUAL PAINT STRIPPING

2 SHIFT OPERATION

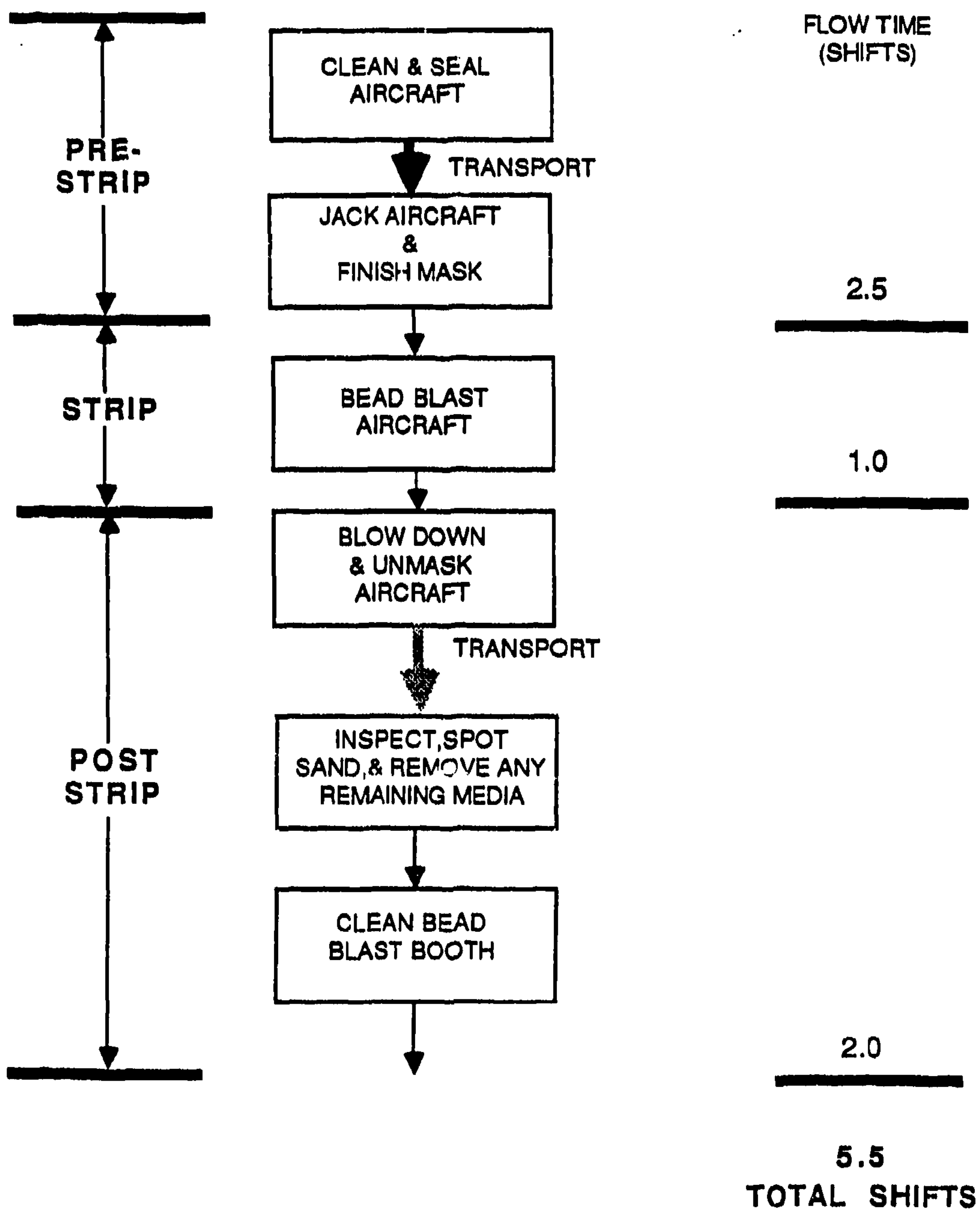


	DIRECT LABOR HOURS	MATERIAL	INDIRECT COSTS
PRE-STRIP	80 HOURS	\$221 (1.-7.)	\$33,929 (9.)
STRIP	70 HOURS	\$2,639 (8.)	\$355 (2.-4.) \$70 (6.) \$29,687 (9.)
POST STRIP	93 HOURS		\$139 (7.) \$39,442 (9.)
	243 DL HOURS \$4,656	\$2,860	\$103,622 (\$564 without Flow Day Costs)

TOTAL BEAD BLASTING COST = \$111.138 / AIRCRAFT

REVISED July 10, 1990

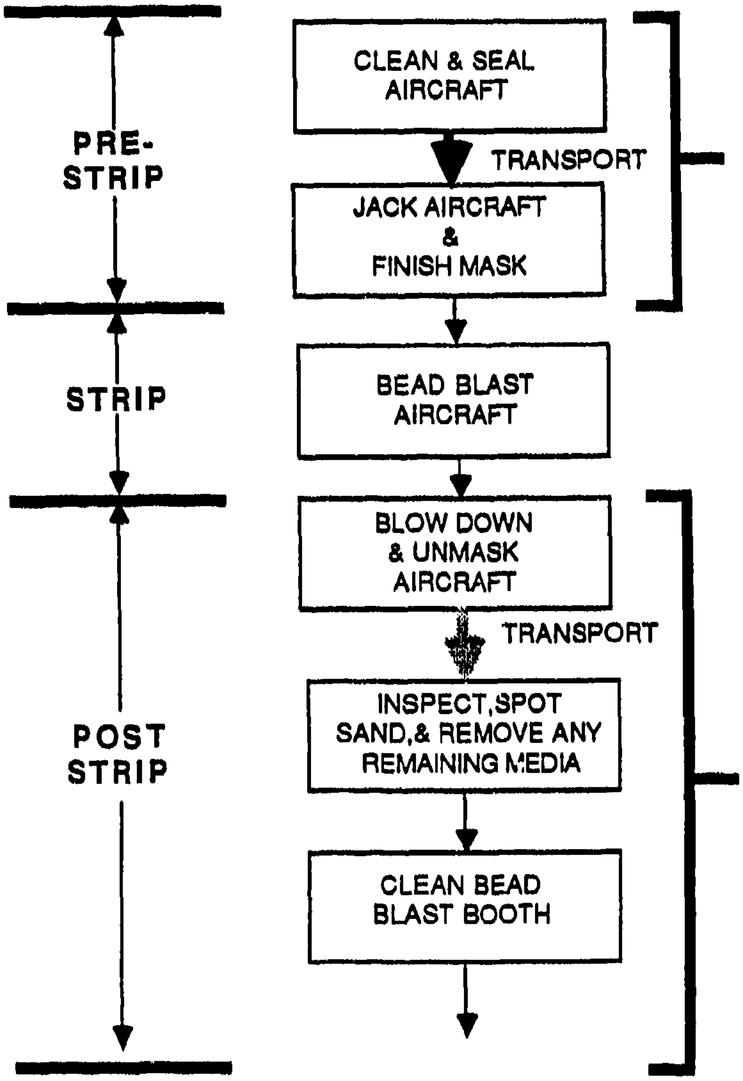
F-16 ROBOTIC PAINT STRIPPING



REVISED July 10, 1990

F-16 ROBOTIC PAINT STRIPPING

2 SHIFT OPERATION



	DIRECT LABOR HOURS	MATERIAL	INDIRECT COSTS
PRE-STRIP	80 HOURS	$221 (1.-7.)	$36,911 (9.)
STRIP	18 HOURS	$1,741 (8.)	$203 (3.-4.) $1,611 (8.) $8,305 (9.)
POST STRIP	91 HOURS		$231 (7.) $41,087 (9.)
	189 HOURS $3,621	$1,962	$89,248 ($3,098 without Flow Day Costs)

TOTAL BEAD BLASTING COST = $94,831 / AIRCRAFT

REVISED July 13, 1990